

**Olfactory Landmark Information in Wayfinding:
Implicit and Explicit Processing of Sensory Information
in Spatial Orientation**

Synopsis zur kumulativen Dissertation

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„If in doubt, always follow your nose.”

– Gandalf, Lord of the Rings

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Summary

Human navigation research has long been dominated by a vision-centered perspective, often neglecting the role of other sensory modalities, particularly olfaction. Across two empirical studies and a state-of-the-art review, this dissertation examines how visual and olfactory cues guide human wayfinding. The first study shows that switching between visual and olfactory landmark information leads to switching costs, reflected in longer decision times and reduced wayfinding accuracy. These results diverge from earlier findings of absent switching costs between auditory and visual landmarks, suggesting that odors and images are initially processed in separate cognitive systems and require cognitively demanding cross-modal translation. The second study demonstrates that olfactory landmarks can support navigation even without explicit recognition. Across two testing times one month apart, wayfinding performance in a virtual maze was highest when olfactory cues were processed implicitly, whereas performance with visual landmarks was higher when processed explicitly. These results suggest distinct implicit mechanisms in the olfactory system and highlight the importance of non-conscious contributions to navigation. The third publication is a review article on the sense of smell in human navigation, summarizing empirical findings, challenging the misconception that humans have a poor sense of smell, and outlining why this ability has been largely overlooked. Together, the studies provide converging evidence that olfactory cues can meaningfully support human wayfinding, largely through implicit processes. Based on these insights, the dissertation proposes a *Multimodal Integrative Model* distinguishing implicit from explicit processes across visual and olfactory modalities, highlighting their joint role in flexible multimodal navigation.

Zusammenfassung

Die Forschung zur menschlichen Navigation wurde lange von einer visuell geprägten Perspektive dominiert und hat dabei die Rolle anderer Modalitäten, insbesondere des Geruchssinns, vernachlässigt. Diese Dissertation untersucht anhand von zwei empirischen Studien und einem Überblicksartikel, die Rolle von visuellen und olfaktorischen Hinweisen beim menschlichen Wegfinden. Die erste Studie zeigt, dass beim Wechseln zwischen visuellen und olfaktorischen Landmarken deutliche Kosten entstehen, die sich in längeren Entscheidungszeiten und reduzierter Navigationsgenauigkeit äußern. Diese Ergebnisse unterscheiden sich von früheren Befunden ohne Wechselkosten zwischen auditiven und visuellen Landmarken und deuten darauf hin, dass Gerüche und Bilder zunächst in getrennten kognitiven Systemen verarbeitet werden und eine anspruchsvolle Übertragung zwischen den Modalitäten erfordern. Die zweite Studie zeigt, dass olfaktorische Landmarken die Navigation auch dann unterstützen, wenn sie nicht bewusst erkannt werden. Über zwei Testzeitpunkte hinweg, die einen Monat auseinanderlagen, zeigte sich, dass das Wegfinden in einem virtuellen Labyrinth eine höhere Genauigkeit aufwies, wenn Geruchsreize implizit verarbeitet wurden, während visuelle Landmarken bei expliziter Verarbeitung zu korrekteren Wegentscheidungen führten. Dies weist auf spezifische implizite Verarbeitungsmechanismen des olfaktorischen Systems hin und unterstreicht die Bedeutung nichtbewusster Prozesse für die Navigation. Die dritte Publikation stellt einen Überblicksartikel zur Bedeutung des Geruchssinns in der menschlichen Navigation dar, der zentrale empirische Befunde zusammenfasst, die Annahme einer schwachen menschlichen Geruchswahrnehmung hinterfragt und erläutert, warum dieses Thema lange wenig Beachtung fand. Die drei Arbeiten liefern zusammen klare Hinweise darauf, dass olfaktorische Reize das menschliche Wegfinden substantiell unterstützen, vor allem durch implizite Prozesse. Auf dieser Grundlage wird ein *Multimodales Integratives Modell* entwickelt, welches implizite und explizite Prozesse im visuellen und olfaktorischen Bereich unterscheidet und deren gemeinsame Rolle in flexibler multimodaler Navigation verdeutlicht.

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Part I.

Olfactory Landmark Information in Wayfinding:

An Overview

1. Introduction

Many animals, such as ants (Steck, 2012), dogs (Thesen et al., 1993), and rats (Rossier & Schenk, 2003), rely on scent to encode and navigate their spatial environment, integrating olfactory cues into their cognitive maps - a concept that will be further elaborated in the context of human navigation below. This demonstrates the powerful and adaptive role of smell in guiding behavior. Humans, too, respond to olfactory stimuli, although often without conscious awareness. In marketing, this influence has been deliberately exploited for decades, with scents being used in supermarkets, shopping centers, and leisure facilities to shape consumer behavior (Emsenhuber, 2009; Fründt, 2010). Yet, it remains unclear to what extent humans also make use of olfactory information for spatial orientation and navigation. To date, scientific research exploring the multimodal connections between olfactory perception and other sensory modalities in human navigation is still limited (e.g., Hamburger & Knauff, 2019).

For a long time, human olfaction was considered to be of little importance, a view originating from 19th-century theories by Paul Broca (1878) and others, who argued that the human sense of smell¹ had regressed through evolution as higher cognitive functions developed (McGann, 2017). However, this assumption has been strongly challenged in recent years. Research has demonstrated that the human olfactory system is far more sensitive and complex than previously assumed. For example, Bushdid and colleagues (2014) estimated that humans can discriminate more than one trillion different odor mixtures, vastly exceeding the approximately two to 40 million discernible colors in vision (Kuehni, 2016; Pointer & Attridge, 1998) and about 330,000 tones in audition (Jacobson, 1950). This finding highlights the remarkable precision of the human olfactory system, whose discriminative capacity even surpasses that of the visual and auditory senses. Such findings demand a reconsideration of its functional role in human life.

The human olfactory system is traditionally understood to serve fundamental functions related to self-preservation, such as locating food, assessing its quality (Yeomans, 2006), and detecting warning

¹ In this dissertation, the terms *sense of smell*, *smell*, and *olfaction* are used interchangeably to refer to the human olfactory sense. Although distinctions are sometimes made - e.g., *olfaction* as the physiological process and *smell* as the subjective experience - these terms are often used synonymously in literature (see Stevenson, 2010; Wilson & Stevenson, 2006).

signals like the smell of fire or toxic substances (Scherer & Quast, 2001). Recent research, however, suggests that the sense of smell may have originally evolved to support spatial orientation (Dahmani et al., 2018), as proposed by Jacobs' olfactory spatial navigation hypothesis (2012, 2019). According to this view, olfaction exerts a "major effect on how we perceive and navigate the world" (Huber et al., 2022, p. 1). Supporting this, experimental studies have demonstrated that humans are capable of navigating through virtual environments based solely on olfactory cues (Hamburger & Knauff, 2019; Jacobs et al., 2015; Schwarz & Hamburger, 2024).

In these studies, so-called *landmarks* served as points of reference. Yet, the majority of existing research focuses primarily on visual landmarks, while olfactory, auditory, and tactile landmark information remains largely underexplored. This is despite Caduff and Timpf's (2008) conceptual framework, which emphasizes that landmarks can be presented in multiple sensory modalities. One reason for this imbalance is that vision has been historically and structurally privileged within cognitive science and psychology. As Hutmacher (2019) argues, vision receives disproportionately more scientific attention than any other sensory modality, partly due to methodological convenience, cultural biases, and the dominance of visually oriented paradigms. This imbalance has not only introduced conceptual and methodological limitations, but in some cases also led to misleading interpretations of results, in part because paradigms originally developed for visual landmarks are often applied uncritically to other sensory modalities (Møller & Köster, 2023).

For example, in literature landmarks are often defined as discrete and distinct objects or features that can be perceived and remembered (Lynch, 1960; Presson & Montello, 1988; Sorrows & Hirtle, 1999). According to this definition, olfactory as well as auditory and tactile cues would appear to play little or no role in human landmark-based navigation, as such cues do not constitute discrete objects in the environment. Moreover, people often cannot consciously identify or verbally label scents (Cain, 1979), which further challenges their classification as landmarks in the traditional sense.

However, in my doctoral research, I deliberately focused primarily on olfactory processing, excluding auditory and haptic modalities, in order to investigate the unique contributions of smell in cognition, using vision, which has traditionally dominated research on navigation, as a comparative reference. Building on this approach, I therefore adopt a broader and modality-independent definition

of landmarks. Specifically, I conceptualize landmarks not as discrete physical objects, but as any stable, detectable environmental cues, whether visual, olfactory, auditory, or tactile, that can support spatial navigation by providing informative reference points (Schwarz & Hamburger, 2023). This functional definition shifts the focus away from objecthood and conscious identifiability and instead emphasizes the informational value a cue provides for navigation.

Although it may seem intuitive that cognitive maps are constructed primarily from visual information, it is crucial to specify what is meant by this concept. Drawing on Tolman (1948) and subsequent spatial cognition research, cognitive maps are internal representations of the spatial relationships among objects and locations within an environment, enabling individuals to navigate and plan routes. While some authors, such as Montello (1998), argue that only certain types of information, typically visual, are incorporated into these maps, growing evidence indicates that humans can integrate cues from multiple sensory modalities, including olfactory, auditory, and tactile information, into their spatial representations (e.g., Fischler-Ruiz et al., 2021; Jacobs, 2012; Orloff & Boorman, 2023). Recent studies (Hamburger & Knauff, 2019; Karimpur & Hamburger, 2016; Schwarz & Hamburger, 2024) provide empirical support against the notion that landmark-based navigation in humans depends exclusively on visual cues.

Building on a systematic literature review and a series of experimental psychology studies, including my master's thesis as a precursor to this doctoral project, I here propose a *Multimodal Integrative Model* of navigation in which sensory modalities are conceptualized as interacting systems rather than as independent perceptual channels, an idea already anticipated by Gibson (1966) in his view of perception as an active and integrated system.

While some evidence supports the hypothesis that humans draw on multiple modalities instead of relying solely on vision when navigating through space (Iggena, et al., 2023; Jacobs, 2012), the overall body of empirical research in this area is still limited. The combination of environmental cues from different modalities and their interaction in supporting navigation has not been systematically examined. Addressing this gap in our current knowledge was therefore the primary aim of the present

dissertation, which seeks to advance our understanding of how multimodal sensory integration shapes human wayfinding².

1.1 The Unique Processing of Odorants

Before addressing the potential role of olfaction in spatial orientation, it is necessary to consider some fundamental aspects of how olfactory information is processed and represented in the human brain. Due to the limited and often ambiguous body of evidence, the psychological foundations of olfactory processing remain thus far poorly understood. Nevertheless, current research suggests that olfaction possesses unique features that distinguish it from other senses (Stevenson & Boakes, 2003), making it a compelling target for future investigations into human perception and the underlying mechanisms of brain function.

One notable characteristic is its close link to emotions (Aggleton & Mishkin, 1986) as well as to experiences and autobiographic memories (Cahill et al., 1995; Schwerdtfeger et al., 1990; Stäubli et al., 1984; White et al., 2015). As early as 1913, the author Marcel Proust described an experience later known as the “Proust phenomenon” (van Campen, 2014), which remains the most famous example of the evocative power of odor and taste: he recounted how the taste of a madeleine dipped in tea unexpectedly and unconsciously triggered a long-forgotten childhood memory (Proust, 1913). Since taste is composed of both olfactory and gustatory stimuli, psychologists and neuroscientists have since examined why odor-evoked memories are unusually emotionally potent. The hypothesis of a unique connection between odors and emotions, initially based on introspection and observation, has been confirmed by neuroimaging studies showing a direct anatomical link between the olfactory cortex and the amygdala-hippocampal complex of the limbic system (Aggleton & Mishkin, 1986). Moreover, studies of human long-term memory have also found that olfactory long-term memory is unusually resistant to decay, and that short-term memory for odors appears to be weak or even absent (Herz & Engen, 1996). One possible explanation is that odors are represented in memory in a uniform manner,

² Navigation can be divided into two conceptually distinct but closely related skills: locomotion and wayfinding. Locomotion refers to real-time movement toward a goal (Montello, 2005), whereas wayfinding involves the strategic, goal-directed process of identifying a destination and planning a route (Lynch, 1960), reflecting the deliberate and purposeful aspect of navigation. The terms navigation and wayfinding are often used interchangeably in the literature and are used synonymously in this dissertation.

which may limit the acquisition of new odors but, due to minimal interference, lead to only slight loss over time (Engen, 1987; Lawless, 1978).

The connection between odors and experiences is further reflected in how olfactory qualities are described (Stevenson & Boakes, 2003). For practical reasons, we usually describe odor qualities by creating odor profiles drawn from memories of previously encountered smells. Stevenson and Boakes (2003) argue that this dependence on prior experiences constitutes a fundamental aspect of olfaction, as the odor qualities are shaped by the memories triggered by the odorants themselves.

From a neuroanatomical perspective, the sense of smell also functions independently from other sensory systems (Herz & Engen, 1996). Olfactory information is the only sensory input that does not pass through the thalamus which is responsible for sensory integration and relay (Farbman, 1992), before being projected to the cerebral cortex (Herz & Engen, 1996). Furthermore, the olfactory system is considered phylogenetically the oldest, most evolutionarily primordial sensory modality and consequently served as the first evolutionary pathway for communication between organisms (Hoover, 2010). Regarding vertebrate brain evolution, the variability in the size of the olfactory bulb is also remarkable, as it does not scale proportionally with overall brain size like other brain regions do (Jacobs, 2012). Although this variability appears to be related to the functional role of the olfactory system, it remains unexplained within the framework of the classical functions of olfaction. This perspective necessitates a broader consideration of the olfactory system's adaptive significance beyond its classical functions, raising the question of whether some of its anatomical and functional variability may reflect evolutionary pressures related to spatial behavior. According to the olfactory spatial hypothesis by Jacobs (2012), if the primary function of the sense of smell were navigation, specifically, predicting the distribution of odorants in time and space, then variation in olfactory bulb size could be attributed to differing navigational demands across vertebrate species. In relation to olfactory memory and navigation, evidence from rodent studies suggests that the anterior olfactory nucleus may contribute to both odor memory (Aqrabawi & Kim, 2018) and localization (Kikuta et al., 2010).

However, overall, studies employing neuroimaging to investigate the human olfactory system are still in their early stages, and odor-based navigation remains rarely examined in current research (Ielo et al., 2025; Kulason et al., 2022; Raithel et al., 2023).

1.2 Implicit versus Explicit Processing of Olfactory Information

Taken together, the evidence discussed so far illustrates that olfaction is a complex and evolutionarily ancient sensory system whose functions extend beyond mere detection of environmental stimuli. Yet, despite growing insight into its neural and cognitive mechanisms, considerably less is known about how these processes manifest in observable behavior. Understanding how olfactory information influences perception, decision-making and action is therefore an essential step in elucidating the broader role of olfaction in human cognition.

While the influence of olfactory cues on behavior is generally acknowledged (e.g., sensory marketing), there is little scientific evidence supporting it, and few systematic studies have examined these phenomena (Degel & Köster, 1999). However, interest in the role of olfaction in cognition is growing rapidly. This is reflected in the fact that the annual conference of the German Psychological Society (DGPs) recently featured, for the first time, a dedicated session on “Olfaction and Cognition” (Bermeitinger & Greve, 2022), that the 2024 TeaP (“Tagung experimentell arbeitender Psychologen”) included a symposium on “Cognitive and Neural Processes Underlying the Perception of Odors” (Fröber et al., 2024), and that the 2026 TeaP will again host a symposium on “Current Topics in Basic and Applied Memory Research”, with a special focus on odor memory. There is also an increasing public and clinical attention to olfactory research. For example, the COVID-19 pandemic highlighted the importance of the sense of smell, prompting olfactory training programs - developed and studied by Prof. Dr. Thomas Hummel and colleagues at the Interdisciplinary Center for Smell and Taste at TU Dresden (Interdisziplinäres Zentrum für Riechen und Schmecken, n.d.) - which have been shown to improve odor perception and associated cognitive processing.

However, research on olfaction faces several challenges that make it more difficult to study compared to other modalities such as the visual system and highlights the need to avoid applying vision-based theories to human olfactory processing (Møller & Köster, 2023). This can also be seen in the large body of literature on visual navigation in humans compared to the relatively small number of studies on olfactory navigation in humans (Hamburger, 2020). One key difficulty is that odors are hard to identify

and, in particular, to label (Wippich et al., 1989; Olofsson & Gottfried, 2015). Moreover, odorants are often processed implicitly and do not always trigger a conscious perception of smell, referred to as an “odor”, which may explain why their significance has historically been underestimated. Nevertheless, it is assumed that even implicitly processed odorants can have a significant influence on our behavior and thinking (Degel & Köster, 1999).

For more than a decade, the research group of Experimental Psychology and Cognitive Science at Justus Liebig University Giessen has investigated the perceptual and cognitive processing of landmark information in human wayfinding, including the use of olfactory cues as landmarks (e.g., Hamburger & Knauff, 2019). Accumulating evidence has emerged that cannot be explained by existing theories, models, or concepts, suggesting that odors may be processed differently from other sensory modalities.

For example, previous studies have reported divergent findings regarding recognition and wayfinding performance (e.g., Hamburger & Röser, 2014, for visual, verbal, and acoustic landmarks). These results led to the conclusion that the cognitive processes underlying landmark-based wayfinding and landmark recognition are distinct and should therefore be investigated separately. Consequently, wayfinding tasks should always be included when studying navigation, rather than relying solely on recognition tasks, as was often done previously. A particularly striking observation emerges for olfactory landmarks: although recognition performance across sensory modalities (i.e., visual, auditory, and olfactory) is typically about ten percent higher than wayfinding performance (Hamburger & Röser, 2014), Arena and Hamburger (2022) found that participants frequently made correct navigational decisions despite failing to recognize olfactory landmarks. Notably, this finding was reported descriptively and was neither experimentally nor statistically tested. So far, this phenomenon has been observed only for olfactory landmarks, suggesting that odor recognition or even identification is not a prerequisite for accurate navigation and indicating that even unconsciously perceived odors may influence performance.

Moreover, earlier studies on “switching costs”, the cognitive costs of switching between modalities within a task (i.e. errors, time), found no decline in performance, measured as the number of correct wayfinding decisions, when switching between auditory and visual landmarks (Hamburger &

Röser, 2011). This finding is consistent with the idea that sensory stimuli such as images and sounds are integrated within the same cognitive system.

In this context, Hamburger (2020) was the first to apply Nobel laureate Daniel Kahneman's dual-system framework (System 1 for implicit, fast, automatic processing and System 2 for explicit, slow, deliberate processing; Kahneman, 2011) to landmark-based wayfinding. In unfamiliar environments, people are likely to use visual landmarks consciously, activating System 2, whereas in familiar settings, landmark use is more likely to occur unconsciously, involving System 1. Similarly, multimodal landmark information can be processed either implicitly or explicitly. I assume that olfactory landmarks are processed automatically within the evolutionarily older System 1, as people are often unable to consciously recall or explicitly name an odor, an assumption that is further elaborated in the *Multimodal Integrative Model* developed in the discussion of this dissertation.

The only studies that have directly investigated implicit olfactory memory (Degel & Köster, 1998, 1999) found evidence for implicitly learned odor memories. In their experiments, participants rated how well odors matched various visual contexts. This design represented the first systematic attempt to measure implicit olfactory memory. Although participants did not consciously perceive the odors presented during the experiment, the odors were implicitly represented in memory. The experiments also showed that when people are unknowingly exposed to an odor, as is often the case in navigation, they later associate that odor with the place where they encountered it, even without awareness of the exposure. Notably, this effect only occurred among participants who could not name the odor; those who could name it showed no such effect (Degel & Köster, 1999). This may indicate that once an odor is stored in semantic memory, it overrides and suppresses implicit memory traces. Consequently, knowing the correct name of an odor could negatively affect wayfinding performance.

Despite the striking nature of these findings, which date back more than two decades, no subsequent studies or theoretical models have investigated or explained the phenomenon reported by Degel and Köster (1998, 1999), nor has it been explored in the context of human navigation.

2. Purpose of the Doctoral Thesis

Given the above and other atypical perceptual as well as neural characteristics, it is reasonable to assume that the human olfactory system differs in many respects from other sensory modalities and thus requires further investigation. Despite its crucial role in wayfinding for many mammals (e.g., Steck, 2012), its contribution to human navigation remains largely unexplored. A search for “olfactory” and “navigation” in the APA PsychNet database (as of December 10, 2025) yielded only ten results, seven of which focused exclusively on animals, highlighting the paucity of human-related research in this field. Nevertheless, the laboratory studies on humans indicate that they are capable of orienting themselves using olfactory cues alone (e.g., Dahmani et al., 2018; Hamburger & Knauff, 2019; Jacobs, 2019). Against this background, investigating the role of the olfactory system in landmark-based wayfinding is crucial for achieving a comprehensive understanding of human navigation and orientation.

The aim of the present doctoral research was therefore to address several interrelated objectives: First, to investigate the multimodal use of landmark information in wayfinding; second, to demonstrate that landmarks do not need to be consciously perceived to support successful navigation; and third, to contribute to closing the gap in cognitive research on odor-based wayfinding by examining whether olfactory landmark information plays a significant role in human navigation.

The central hypothesis was that, unlike other senses, the human sense of smell is predominantly used implicitly in wayfinding.

Accordingly, the work systematically examined the implicit influence of odors on human landmark-based navigation and explored the existence of implicit olfactory memory. While vision remains the dominant sense in human navigation, this dissertation sought to provide a more holistic understanding of multisensory navigation. The findings could lead to new insights and a deeper understanding of olfactory consciousness, as well as advance the development of experimental methods for assessing implicit odor memory.

3. Overview of the Present Research

3.1 Publication 1

Schwarz, M., & Hamburger, K. (2022). Modality Switching in Landmark-Based Wayfinding.

Frontiers in Psychology, 13, 888871. <https://doi.org/10.3389/fpsyg.2022.888871>

3.1.1 Purpose of Publication 1

The purpose of the first publication was to investigate the cognitive mechanisms involved in modality switching during landmark-based wayfinding, focusing on visual and olfactory landmark information. Earlier studies have shown that switching between visual and auditory modalities does not impair navigational performance, suggesting shared cognitive processing between these senses. Whether this also applies to olfaction remained unclear.

Building on theoretical accounts proposing that olfactory information is processed in a distinct and evolutionarily older system, the study examined whether switching between visual and olfactory cues leads to measurable cognitive costs during spatial orientation. Participants navigated a virtual environment in which landmark and directional information were presented either in the same or in different sensory modalities across learning and recall phases. By comparing wayfinding accuracy and decision times between switching and non-switching conditions, the study aimed to clarify how sensory information from different modalities is integrated during human navigation.

The broader goal of this research was to contribute to a more differentiated understanding of how sensory information is integrated during human navigation and to test the assumption that olfactory cues are processed independently from visual cues. Demonstrating switching costs between olfactory and visual modalities would provide behavioral evidence for the existence of distinct cognitive systems for different sensory modalities, thereby challenging vision-centered models of spatial cognition and highlighting the functional significance of olfactory research in human navigation.

3.2 Publication 2

Schwarz, M., & Hamburger, K. (2023). Implicit versus explicit processing of visual, olfactory, and multimodal landmark information in human wayfinding. *Frontiers in Psychology, 14*, 1285034. <https://doi.org/10.3389/fpsyg.2023.1285034>

3.2.1 Purpose of Publication 2

The purpose of the second publication was to empirically examine the role of the human sense of smell in landmark-based navigation, with a particular focus on its implicit processing. As mentioned above, previous research in spatial cognition has been dominated by studies on visual perception, however, emerging evidence suggests that olfaction can also guide navigation, especially when processed outside of conscious awareness. Building on this idea, the study aimed to answer the question whether implicitly perceived olfactory landmarks would enhance wayfinding performance compared to explicitly perceived olfactory landmarks, and how these effects compare to visual and multimodal landmark conditions. By systematically manipulating the sensory modality (olfactory, visual, multimodal) and the mode of processing (implicit vs. explicit) across two times of testing, this study sought to uncover distinct cognitive mechanisms underlying olfactory versus visual landmark use. The broader goal was to provide empirical support for the hypothesis that olfactory navigation relies on unique, predominantly implicit processing pathways, thereby expanding current theoretical models of spatial cognition beyond a vision-centered perspective. In doing so, the study contributes to closing a major gap in literature and lays the groundwork for developing experimental paradigms capable of capturing implicit sensory processing across modalities - an essential step toward a more comprehensive understanding of human consciousness and behavior.

3.3 Publication 3

Schwarz, M., Yang, A. L., & Hamburger, K. (2025). The human sense of smell in spatial orientation: A state-of-the-art review. *Psychology of Consciousness: Theory, Research, and Practice*, 12(2), 169–185. <https://doi.org/10.1037/cns0000395>

3.3.1 Purpose of Publication 3

The final publication of this doctoral thesis served as an integrative conclusion, providing a comprehensive theoretical overview of the role of the human sense of smell in navigation, with particular emphasis on its predominantly implicit nature. Historically, human olfaction has been underestimated due to the persistent misconception that humans possess a poor sense of smell. By synthesizing evidence from comparative research with nonhuman animals, cognitive neuroscience, and behavioral studies, this review aimed to challenge this misconception and highlight the evolutionary plausibility of olfactory navigation in humans. The article discusses why olfactory processing in navigation is likely to occur primarily outside of conscious awareness, how this implicitness has contributed to its neglect in past research, and which neurocognitive mechanisms may underlie it. In addition, it explores the emotional salience and memorability of olfactory cues in comparison to visual cues, proposing that these unique characteristics make olfaction a valuable yet overlooked modality in spatial cognition. Beyond navigation, the review identifies potential applications of olfactory research in domains such as aromatherapy, environmental design, and early diagnosis of neurodegenerative diseases like Alzheimer's. By integrating these perspectives, the publication not only embeds the key findings and conceptual contributions of this dissertation into the existing research on human olfaction and navigation, but also seeks to foster further empirical work and promote interdisciplinary applications of olfactory science.

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Part I

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Part II.

Publications of the Cumulative Dissertation

5. Modality Switching in Landmark-Based Wayfinding³

5.1 Abstract

This study investigates switching costs in landmark-based wayfinding using olfactory and visual landmark information. It has already been demonstrated that there seem to be no switching costs, in terms of correct route decisions, when switching between acoustically and visually presented landmarks. Olfaction, on the other hand, is not extensively focused on in landmark-based wayfinding thus far, especially with respect to modality switching. The goal of this work is to empirically test and compare visual and olfactory landmark information with regard to their suitability for wayfinding including a modality switch. To investigate this, an experiment within a virtual environment was conducted in which participants were walked along a virtual route of 12 intersections. At each intersection, landmark information together with directional information was presented, which was to be memorized and recalled in the following phase, either in the same or in the other modality (i.e., visual or olfactory). The results of the study show that, in contrast to the no-switching costs between auditory and visual landmarks in previous studies, switching costs occur when switching modality from visual to olfactory and vice versa. This is indicated by both longer decision times and fewer correct decisions. This means that a modality switch involving olfactory landmark information is possible but could lead to poorer performance. Therefore, olfaction may still be valuable for landmark-based-wayfinding. We argue that the poorer performance in the switching-condition is possibly due to higher cognitive load and the separate initial processing of odors and images in different cognitive systems.

³ Schwarz, M., & Hamburger, K. (2022). Modality Switching in Landmark-Based Wayfinding. *Frontiers in Psychology, 13*, 888871. <https://doi.org/10.3389/fpsyg.2022.888871>

5.2 Introduction

Every day, people are challenged to get from their current location to a destination, whether it is finding their way home from a train station or just locating the nearest supermarket. Navigating through our environment thus represents an everyday task in human as well as animal life. Here, Montello (2005) makes a distinction between two components of navigation, which were also taken up by Montello and Sas (2006): Wayfinding and locomotion. Wayfinding is described as “the efficient goal-directed and planning part of navigation” (Montello and Sas, 2006, p. 2) and is therefore directly associated with problem solving. In addition, locomotion is the “real-time part of navigation” (Montello and Sas, 2006, p. 2), in which we try to avoid obstacles and arrive at our destination without further complications. In conclusion, navigation is a combination of wayfinding, i.e., route planning, which is the cognitive component, and locomotion, i.e., the process of moving along the route.

As soon as we are planning a route, we orientate ourselves on the basis of streets, buildings, or other objects (e.g., street signs, statues and the like). However, it is not just visual landmarks which play an important role even though research in landmark-based wayfinding mainly focusses on the visual aspects in human navigation (e.g., Lynch, 1960; Presson and Montello, 1988; Sorrows and Hirtle, 1999). Holden and Newcombe (2013) introduce a model of combining a variety of sources based on evidence concerning their validity. In this model, the reliability of spatial estimation accuracy increases when different modalities (i.e., auditory and visual cues) are combined in a Bayesian framework (Holden and Newcombe, 2013). The impact of non-visual elements coupled with visual elements on human spatial cognition has hardly been investigated. However, the explanatory approach of Holden and Newcombe (2013) was recently taken up by Siepmann et al. (2020) in a study indicating effects of sound positions in maps as cues for spatial memory performance.

Orientation by smell is mainly associated with species other than humans. In the animal kingdom, the ability to orientate by olfactory information has been demonstrated primarily in desert ants (e.g., Steck et al., 2009, 2011; Steck, 2012), rats (e.g., Rossier and Schenk, 2003) and dogs (Hepper and Wells, 2005; Reddy et al., 2022). Even untrained ring-tailed lemurs are able to track odor plumes, disproving the traditional belief that primates are unable to do so (Cunningham et al., 2021). Our own

research has repeatedly addressed this bias towards vision in human spatial cognition research (e.g., Hamburger and Knauff, 2019) and demonstrated that humans are also able to orient themselves with auditory, visual verbal (i.e., words visually presented on screen) as well as olfactory cues (e.g., Röser et al., 2011; Hamburger and Röser, 2014; Karimpur and Hamburger, 2016; Hamburger and Knauff, 2019).

Apart from wayfinding research, several studies in other research fields are often concerned with switching costs. Switching costs, or more precisely within-task switching costs, are costs that arise when information from a certain task is presented to the user in a different sensory modality than expected (Kotowick and Shah, 2018). In addition to the within-task switching costs, there is also a cost for switching between tasks in which a different task has to be performed than the one that was initially learned (Arbuthnott and Woodward, 2002). This means that the modality remains the same, but the task changes. However, in wayfinding, information is not always available in the same modality in which we learned it (i.e., unimodal processing). So, what happens when the task stays the same (e.g., finding the correct path) but the modality switches (e.g., from visual to auditory information) within this task? What cognitive costs occur when we need to switch from one processing modality to another? In wayfinding research, it has been shown that there are no or hardly any switching costs in wayfinding performance (i.e., correct route decisions) when comparing visual and auditory landmark information within a wayfinding task (Hamburger and Röser, 2011). However, as mentioned above, olfactory information may also be of relevance and should not be underestimated (e.g., Hamburger and Karimpur, 2017). Are people able to alternate, i.e., switch modality, between vision and olfaction without additional cognitive costs, i.e., more time required or more errors? In the following, wayfinding with modality switches between visual and olfactory landmarks are compared to wayfinding without a modality switch. The results could be of interest especially in the field of interventions for elderly people and people with impaired vision, for whom it is necessary to deal with a specific modality, which is often required especially in unfamiliar environments (Hamburger, 2020).

People orientate themselves to their immediate environment in order to arrive at their destination. One core aspect in human orientation are orientation points, so-called landmarks (for review see Yesiltepe et al., 2021). A landmark is described by Lynch (1960) as any object that potentially serves as a reference point. Accordingly, a variety of different reference points can serve as landmarks,

including trees, traffic lights, but also buildings or man-made objects (for an overview, see for example Lynch, 1960; Golledge, 1999).

The fact that landmarks can have a positive effect on wayfinding performance was shown by Sharma et al. (2017). In this study participants were given a wayfinding task that included a condition with and a condition without landmarks. The participants of the landmark condition made fewer mistakes and required less time on average compared to the participants of the condition without landmarks (Sharma et al., 2017).

The relevance of visual landmarks was demonstrated by, for instance, Denis et al. (2014) who compared routes with and without visual orientation points. Students learned either a route through an urban environment without visual references or a route in a neighborhood with many local stores and urban objects. Participants exposed to the landmark-rich environment with photographs of scenes along the route provided higher recognition scores and shorter decision times than participants who were not presented with visual references. In this case, visual landmarks had a positive impact on participants' performance.

Human wayfinding with different sensory modalities than vision was tested by Hamburger and Röser (2014) who used different modalities to guide participants through a virtual maze. Their participants were divided into three experimental groups (visual, verbal or acoustic) and had to remember a route with the help of either visual, verbal or acoustic landmarks coupled with directional information. In the wayfinding phase, they had to indicate the correct direction at each intersection based on the landmark information given in the previous learning phase. Contrary to what might be expected, the participants showed a similar level of wayfinding performance for all three conditions. Visual, verbal, and acoustic information successfully constituted landmark information. Thus, human wayfinding can be supported not only through visual (e.g., Denis et al., 2014), but also non-visual landmark information (e.g., Hamburger and Röser, 2014).

This again supports the assumption that visual landmarks are not the only helpful means for finding one's way. Therefore, other modalities should also be taken into account. Unfortunately, studies on human olfaction are rare in spatial cognition research. Nevertheless, to illustrate the current state of research on human wayfinding including olfactory landmarks we provide a few exceptions here.

Part II

Dahmani et al. (2018) found an intrinsic relationship between olfaction and spatial memory which is probably rooted in the parallel evolution of the olfactory and hippocampal systems. Porter et al. (2007) found out that humans are able to follow a scent path just like rats and dogs do and are able to become better with practice. Furthermore, Jacobs et al. (2015) showed that humans are able to return to a previously learned location on a map with the help of olfactory cues only. This finding suggests that humans might use this odor-map as mechanism for navigation, too. An experiment by Hamburger and Knauff (2019) has shown that olfactory landmark information can be considered in the context of human wayfinding as well. They investigated this question in order to gain a more comprehensive understanding of the wayfinding ability of people with the help of olfactory information. In their study participants were walked through a virtual maze in which odors were presented as landmark information. At each intersection they had to memorize and later recall the olfactory information. It was demonstrated that participants were able to use the olfactory information to find their way (i.e., wayfinding performance was clearly above chance level). Further, olfactory landmarks have also been addressed in studies on how visually impaired people navigate in everyday life (Koutsoklenis and Papadopoulos, 2011).

Another relevant aspect regarding landmark-based wayfinding is modality switching and possibly associated switching costs. In the following, we refer to the within-task switching costs mentioned above (Kotowick and Shah, 2018) that arise when the task remains the same but the used modality changes (e.g., a picture of a clove of garlic is learned, but orientation must be based on the smell of garlic).

Hamburger and Röser (2011) dealt with the question of whether a modality switch between learning and recalling routes results in additional cognitive costs, i.e., more time required for the route decisions or more incorrect decisions. They contrasted different constellations of a modality switch of visual, acoustic and (visual) verbal landmarks. In the learning phase, either animal words, or sounds, or pictures had to be learned. In a subsequent wayfinding phase, introducing a modality switch or not (e.g., visual → acoustic, visual → visual), landmarks had to be recalled and with their help the way should be found. In none of the constellations additional switching costs occurred. Only the comparison of visual and (visual) verbal landmarks revealed differences in decision times.

Part II

Furthermore, Karimpur and Hamburger (2016) also investigated the wayfinding performance of participants using animal pictures and sounds. The difference to the previous study, however, was that they were not just concerned with unimodal but also multimodal processing. Similar wayfinding performances were found independent of whether participants were confronted with congruent stimuli (e.g., image of a dog paired with the barking of a dog) or incongruent stimuli (e.g., image of a dog paired with the chirping of a bird). Improved performance was demonstrated in the multimodal condition compared to the unimodal condition, which, according to Karimpur and Hamburger (2016), could be due to activation of both the visual and auditory sensory channels and therefore result in more elaborate representations or just better access to the stored information.

Kotowick and Shah (2018) also addressed the issue of modality switching. More specifically, they investigated the question of whether switching modality during navigation using navigation devices has certain advantages. They examined a system that switches between visual and haptic navigation guidance. Temporarily, performance deteriorated, but switching modalities seems to be beneficial for longer navigation tasks and to reduce both habituation effects and stimulus-specific adaptation.

In the following study, switching between visual and olfactory landmark information is contrasted with no-switch conditions in order to shed light on possible modality switching costs in landmark-based wayfinding.

Based on the theoretical and empirical background, it can be assumed that a modality switch is accompanied by none or marginal switching costs. However, it is important whether switching costs are defined as correct route decisions (i.e., correct turns) or as the time required for decision-making. The time required can be differentiated between the initial processing time and the time required to retrieve the correct route decision. Studies show that response times in the olfactory system range from 600 to 1,200 ms (Cain, 1976), which is significantly longer than the 200 ms interval observed for visual, auditory and tactile stimuli (Spence et al., 2000). People can respond to visual stimuli as early as 100 ms apart (Posner and Cohen, 1984), whereas the perception of odors is typically studied at 20–30 s intervals. The temporal resolution here is therefore 200 times greater for odor perception than for visual perception. The initial processing time is thus longer for olfactory than for visual inputs (Cain, 1976;

Spence et al., 2000), whereas there should be little difference in the time required to retrieve the correct response, given the previous research in this area (e.g., Hamburger and Röser, 2011).

For this reason, it was hypothesized that a modality switch in the “switch” condition will result in (1) significantly higher decision times compared to the “no switch” conditions. Furthermore, based on the previous findings in other modalities [auditory, visual, and (visual) verbal] it was expected that the “switch” condition will result in (2) the same relative number of correct decisions compared to the “no switch” conditions. The experiment was based on a one factorial between-subjects design with four levels. The independent variable varied whether a modality switch occurred or not (“switch” vs. “no switch”). In the “no switch” condition, olfactory landmarks were presented to one group and visual landmarks to another in the learning and wayfinding phase. The “switch” condition was also divided into two groups that differed in the modality at learning and test (olfactory → visual vs. visual → olfactory). The dependent variables were the participants’ decision times on the one hand and the relative number of correct decisions on the other.

5.3 Materials and Methods

5.3.1 Participants

A total of 30 students (17 females and 13 males) of the Justus Liebig University were tested. The age range of the participants was 19–66 years ($M = 24.80$, $SD = 8.53$).

Exclusion criteria included any type of restriction in the ability to smell, such as respiratory problems or flu-like infections. Further exclusion criteria included epilepsy and non-corrected visual impairment. Participants were informed in advance to avoid spicy food and smoking on the day before the experiment, as this could have impaired the ability to smell. In addition, the participants were not supposed to use perfume before and during the experiment to ensure that no distraction due to additional odors occurred. Participation was voluntary and was compensated with course credits if required. All participants were naïve with respect to the research question and provided informed written consent prior to participation. The study was approved by the local ethics committee (Department of Psychology, JLU; 2014-0017).

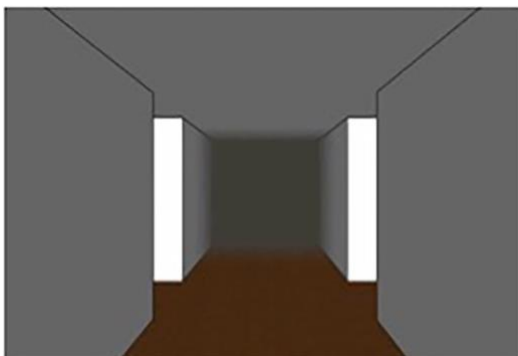
5.3.2 Material

The program OpenSesame 3.2.8 (Mathôt et al., 2019), was used to present routes with 12 orthogonal intersections and for data recording. In total, there were three different route sequences. Participants were pseudo-randomly assigned to the different experimental conditions.

For the creation of the routes, a screenshot of an empty intersection taken from two studies by Hamburger and Röser (2011, 2014) was used (see Figure 1). Furthermore, for the purpose of the study, additional images and the corresponding odor samples were required. The odors were taken from the study by Hamburger and Knauff (i.e., garlic, strawberry, cinnamon, aftershave, etc.; for further details, such as an evaluation of the odors, see Hamburger and Knauff, 2019). The odors used were those with the highest identification rates from a set of 44 odors. Odors were stored in amber glass vials. Since the odors and the images should match, images of objects matching the above odors were taken with a Samsung NX1000 SLR camera. Since participants were presented with either visual or olfactory landmark information, either images of objects implemented in the screenshot (visual landmark condition) or the screenshot of an empty intersection (Figure 1) only (olfactory landmark condition) were presented to the participants. The visual landmarks were placed in the center of the upper half of the virtual room to give the impression that the image was hanging on the ceiling of the intersection in front of the participant. If the participant was assigned to the olfactory condition, she was presented with an odor manually by the experimenter instead of the visual landmark while looking at the empty intersection. The sequence was randomized in advance.

Figure 1

Screenshot of an (empty) intersection taken from Hamburger and Röser (2011, 2014).



In addition, a self-generated light gray arrow was inserted at each intersection (in the visual as well as the olfactory landmark condition) to indicate the direction. The arrow was also located in the center, but in the lower half of the virtual space. The direction in which the arrow pointed at each intersection was also pseudo-randomized.

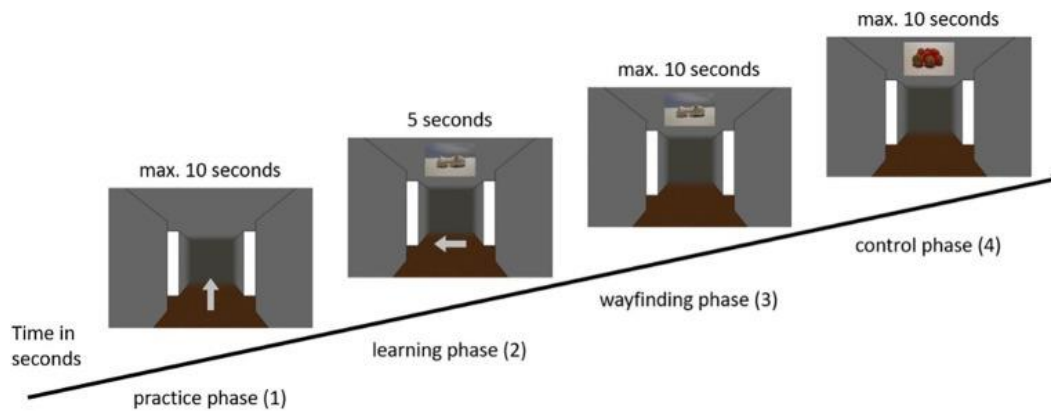
The experiment was run on an Acer Aspire V17 Nitro with a 7th generation IntelCore i7 processor (16GB RAM). The laptop was connected to a Samsung 74-inch 4 K LED flat screen *via* HDMI. A large screen was deliberately chosen to make the environment more realistic and to ensure a stronger immersion effect. Participants provided their decisions using the numeric keypad of an external computer keyboard (1 = left, 2 = straight ahead, 3 = right).

5.3.3 Procedure

Upon arrival participants were asked to sit at a table at the end of the room, where the screen was placed. The distance between the participants and the TV was approximately 60 cm. The only thing that was varied was that the computer keyboard in front of the test person so that it was easily accessible with their hands. In addition to the informed written consent form and an instruction about the experiment, demographic data were collected. Regardless of which condition the participants were assigned to, the main experiment consisted of four phases, the practice phase (1), the learning phase (2), the wayfinding phase (3), and a randomized control phase (4). For clarification, the complete sequence of the main phases is visualized in Figure 2. Before each of these phases, the participants were presented with a detailed instruction, which they were asked to repeat orally in their own words to ensure that they understood the instruction. The instruction included an explanation of the duration of the experiment, the number as well as the sequence of the phases. In addition, each instruction included an explanation of the use of the numeric keypad and a reminder to both focus attention on the center of the screen and to make decisions as quickly and accurately as possible.

Figure 2

Example sequence of the main phases of the experiment in the visual condition (visual → visual).



(1) The first phase of the experiment was a practice phase. Each participant was led through nine trials in which she was presented only with the screenshot of the intersection with a light gray arrow in the middle. There was no presentation of visual or olfactory landmarks in the practice phase. The arrows pointed equally often either to the left, straight ahead, or to the right. Before each intersection, participants were presented with a fixation dot for 3 s to direct their attention to the following intersections. The task was to correctly respond to the presented arrow keys (1 = left, 2 = straight ahead, 3 = right) using the numeric keypad. This gave the participants the opportunity to familiarize themselves with the procedure, the virtual room and the required material, i.e., the numeric keypad of the keyboard. At the end of the practice phase, each participant was presented with feedback showing the average decision time of the trials and the average of correct route decisions in percent. The values of the feedback had no influence on the main part of the experiment that was carried out afterwards.

(2) The practice phase was followed by the learning phase, in which the participants were presented with 12 intersections. In this phase, as well as in each subsequent phase, the participants first saw a blank gray screen for 5 s, in which attention to the screen was not yet required. After that, the participants were presented with a fixation dot for another 3 s, to which the participants were asked to direct their attention. Subsequently, the respective intersection of the participant's individually assigned route appeared. Depending on the condition assigned, participants were presented with either visual or olfactory landmark information. The task was to remember the presented landmark information with the

associated direction, with each landmark (either visual or olfactory) being presented for 5 s. This procedure was based on Karimpur and Hamburger (2016), who gave the participants a maximum of 5 s to decide on directional information in a similar experiment. This was done for each of the 12 intersections. As soon as the test person had completed all 12 intersections, the learning phase ended (for an example trial of the learning phase in the visual condition see Figure 3; for the olfactory condition see Figure 4, for a schematic illustration of the wayfinding phase see also Hamburger and Knauff (2019)).

Figure 3

Example sequence of a single pass in the learning phase of the visual condition (visual → visual).

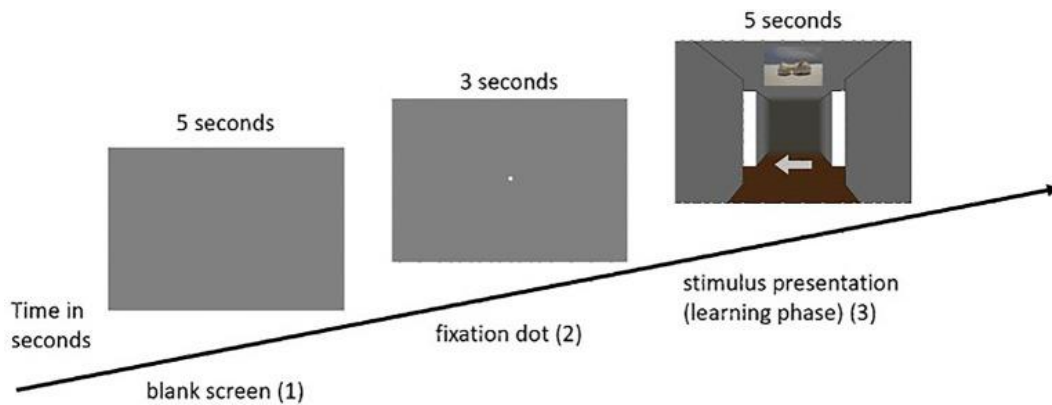
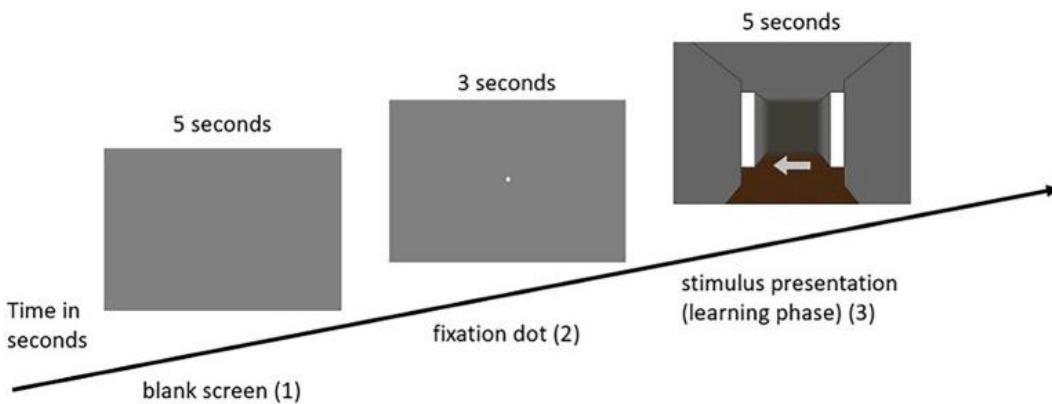


Figure 4

Example sequence of a single pass in the learning phase of the olfactory condition (olfactory → olfactory).



(3) The next phase was the so-called wayfinding phase. Here, the participants were presented with the same route sequence as in the learning phase. The difference, however, was that in the wayfinding phase (either visual or olfactory, see Figures 3, 4) the presentation of the arrows, i.e., the directional information, was omitted. Participants in the “no switch” condition were presented with landmark information in the same modality, while participants in the “switch” condition were presented with corresponding landmark information in the other modality. Once the landmark was presented to the participant, her task was to respond with the associated direction key. In this phase, the landmark information (either visual or olfactory) was presented for a maximum of 10 s. If the participant has already made a decision before the time expired, the experiment went on without interruption and the gray screen appeared followed by the fixation dot and the next intersection. The same applied if the participant did not make the correct decision. The experiment also went on without interruption by the appearance of the gray screen followed by the fixation dot and the next intersection.

(4) The final phase of the experiment was the randomized control phase. Here, the previously learned intersections (i.e., combination of landmark and directional information) were tested again within the same modality as in the wayfinding phase, but in a randomized order. The randomization of the intersections made it possible to compare the third and fourth phase and to check whether the respondent had linked the landmarks to the directions or had learned the path sequentially. After the last phase with again 12 intersections, the main experiment was completed. The duration of the experiment was between 30 and 45 min.

5.4 Results

5.4.1 Switch vs. No Switch

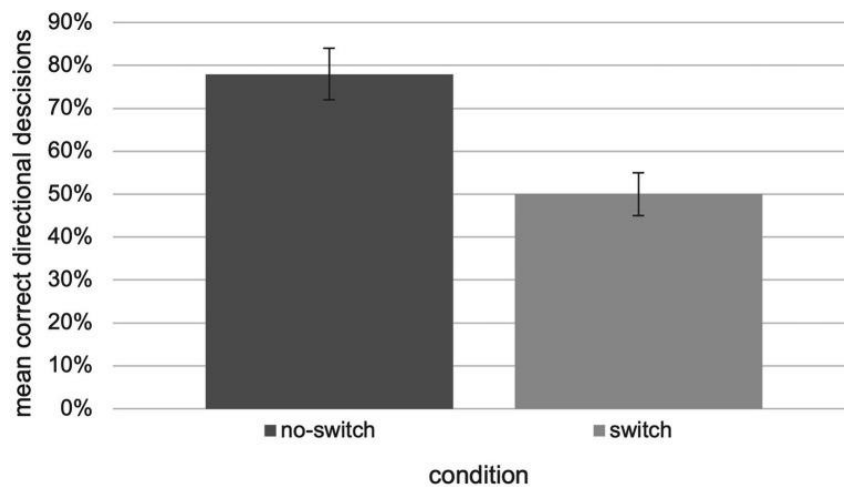
For the question of whether switching costs occur when switching between visual and olfactory landmark information, the following results were obtained. Significances, as well as effect sizes, are reported. Because of the small sample size in each group the test assumption of normal distribution was not given for all groups and conditions. However, while the normal distribution assumption is theoretically important for unpaired t-tests, numerous studies have practically shown that t-tests are relatively robust to violations of normal distribution assumption (e.g., Rasch and Guiard, 2004; Wilcox,

2012). That is why, independent t-tests will still be reported in this study. Additionally, non-parametric Mann–Whitney-U-tests were calculated for the most important results of the study and are reported in brackets.

Wayfinding performance, in terms of the relative number of correct decisions, for the “no-switch” condition ($M=0.78$, $SEM=0.06$) was higher than for the “switch” condition ($M=0.50$, $SEM=0.05$). These findings are visualized in Figure 5. The collected data were analyzed using an independent two-tailed t-test which revealed significant differences between the “no-switch” and “switch” condition, $t(27.35) = 3.38$, $p = 0.002$, $d = 0.931$ [$U = 46.00$, $Z = -2.78$, $p = 0.005$; according to Cohen, 1988 effect sizes are interpreted as follows: small effect size $d = 0.2$, medium effect size $d = 0.5$, large effect size $d = 0.8$].

Figure 5

Relative number of correct decisions with respect to the “switch” and “no switch” condition of the tested experiment ($N = 30$, error bars = SEM).

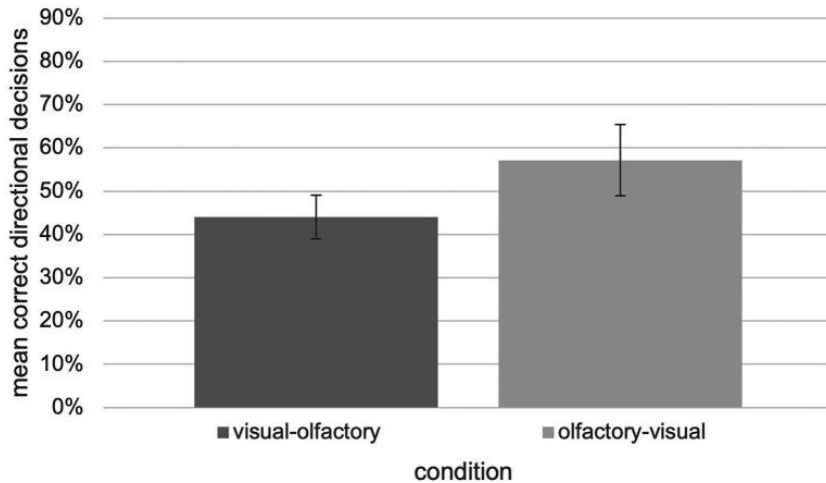


In general, it turns out that a modality switch between visual and olfactory landmark information is possible since performance is significantly above chance level as shown by an one-sample t-test, $t(13) = 3.535$, $p = 0.004$, $d = 0.186$. This result is independent of the switch-direction as an independent two-tailed t-test which revealed no significant differences between the “visual → olfactory” and “olfactory → visual” “switch” condition, $t(12) = -1.357$, $p = 0.20$, $d = 0.180$ ($U = 15.00$, $Z = -1.236$,

$p = 0.217$). However, the “switch” condition seems to be associated with further cognitive costs in terms of a lower number of correct decisions (Figure 6).

Figure 6

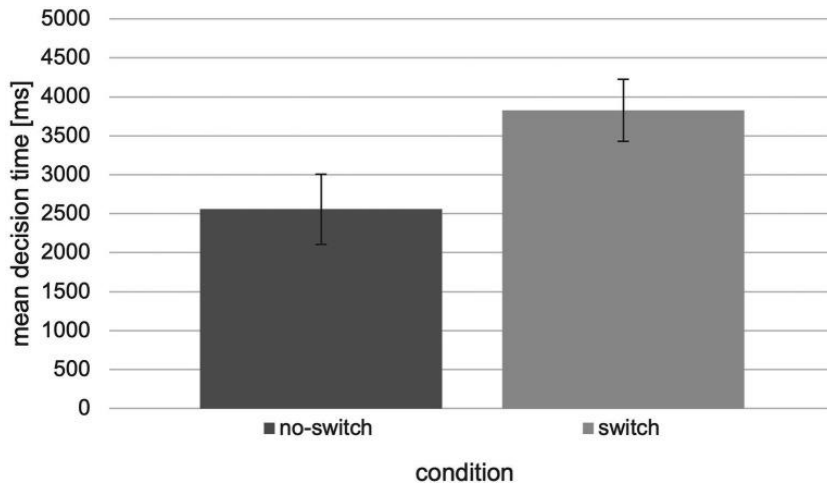
Relative number of correct decisions with respect to the “visual-olfactory” and “olfactory-visual” switch condition of the tested experiment ($N = 30$, error bars = SEM).



Besides the higher performance in terms of correct decisions, there are also shorter decision times for the “no-switch” condition ($M = 2557.70$, $SEM = 446.98$) compared to the “switch” condition ($M = 3827.84$, $SEM = 395.21$; Figure 7). The collected data were also analyzed in terms of mean decision times using an independent two-tailed t-test and revealed significant differences between the “no-switch” and “switch” condition, $t(28) = -2.10$, $p = 0.045$, $d = -0.769$ ($U = 60.00$, $Z = -2.162$, $p = 0.031$).

Figure 7

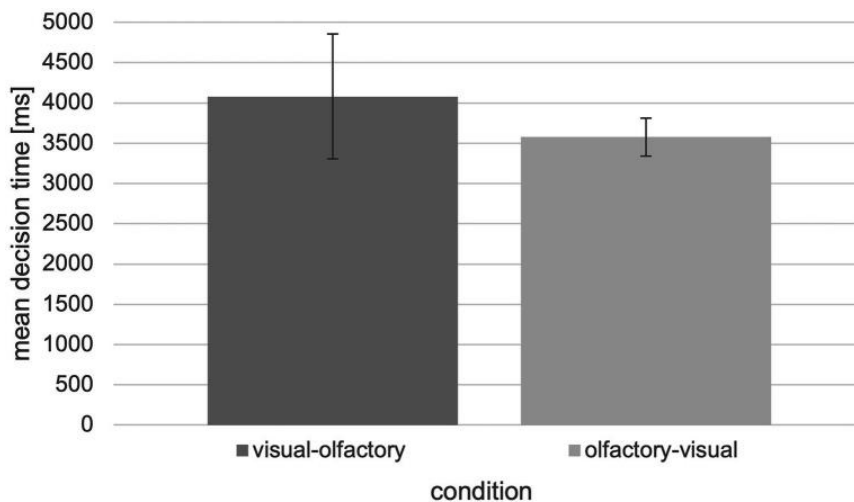
Mean decision time in ms with respect to the “switch” and “no switch” condition of the tested experiment ($N = 30$, error bars = SEM in ms).



In this case, it is also possible to switch between olfactory and visual landmark information, but this is associated with longer decision times (Figure 8).

Figure 8

Mean decision time in ms with respect to the “visual-olfactory” and “olfactory-visual” condition of the tested experiment ($N = 30$, error bars = SEM in ms).



To test the extent to which participants oriented themselves using the landmark information and did not learn the route sequentially, a paired-samples t-test between wayfinding performance in terms

of the relative number of correct decisions in the wayfinding phase and the control phase was conducted and showed a non-significant result, $t(29) = 0.872, p = 0.391$. This implies that the performance between the wayfinding phase and the subsequent randomized control phase is comparable and thus sequential learning of the route on the part of the participants can be ruled out. In the case of sequential learning, participants would have learned only the directional information without a connection to the presented landmark information, and in the case of randomized presentation of the landmark information, the control phase performance would have had to be at chance level.

5.4.2 Comparison of All Levels

In addition to comparing the no-switch and switch conditions, comparisons were also made between all levels present, both for the relative number of correct decisions with $F(3,26) = 22.425, p < 0.001, f = 1.608$ [according to Cohen, 1988 effect sizes are interpreted as follows: small effect size $f = 0.1$, medium effect size $f = 0.25$, large effect size $f = 0.4$], and the mean decision times with $F(3,26) = 10.362, p < 0.001, f = 1.094$.

The comparison of the relative number of correct decisions between the visual ($M = 0.972, SEM = 0.048$) and olfactory groups ($M = 0.524, SEM = 0.054$) in the no-switch condition, showed a significant difference, $t(26) = -6.176, p < 0.001, r = 0.771$ ($U = 0.000, Z = -3.440, p < 0.001$) [according to Cohen, 1988 effect sizes are interpreted as follows: small effect size $r = 0.1$, medium effect size $r = 0.3$, large effect size $r = 0.5$]. Based on the higher relative number of correct decisions, it can be concluded that visual landmarks are better suited for wayfinding than olfactory landmark information.

The participants of the visual “no-switch” condition also seems to have a better performance (i.e., a higher number of correct decisions) in comparison with the participants of the visual-olfactory (“switch”) condition $t(26) = -7.324, p < 0.001, r = 0.821$ ($U = 0.000, Z = -3.440, p < 0.001$) and the participants of the olfactory-visual (“switch”) condition, $t(26) = -5.520, p < 0.001, r = 0.735$ ($U = 6.00, Z = -2.829, p = 0.005$).

The mean decision times of the two “no-switch” conditions visual ($M = 1249.19, SEM = 414.90$) and olfactory ($M = 4240.07, SEM = 470.40$) also differed significantly from each other, $t(26) = 4.769, p < 0.001, r = 0.683$ ($U = 0.000, Z = -3.334, p < 0.001$).

5.5 Discussion

In general, it turns out that a modality switch between visual and olfactory landmark information is possible since performance is significantly above chance level. In contrast to the switching costs between modalities other than olfaction, a modality switch between visual landmarks and olfactory landmark information seems to be associated with further cognitive costs in terms of a lower number of correct decisions.

First, it can be said that it was possible for participants to switch between visual and olfactory landmark information in a wayfinding task. Our results imply that humans may very well use their sense of smell to orientate and navigate. According to Cunningham et al. (2021), the ability to track olfactory plumes may have been an important skill in foraging. However, this incurred additional cognitive costs, which manifested themselves in the form of a lower relative number of correct decisions and higher mean decision times. This is surprising given the empirical data for switching costs in other modalities. Since, for instance, Hamburger and Röser (2011) showed no switching costs in the performance when switching modality from auditory to visual and vice versa.

This could be explained by the fact that auditory information engages both the phonological loop and the visuospatial sketchpad of working memory (Baddeley and Hitch, 1974; Tranel et al., 2003). This would mean that sounds are also initially processed in a different modality as well, namely as images. Thus, there would be an advantage for switching between both modalities within a wayfinding task, as no additional cognitive resources would be required to transfer the learned information into the other modality. In this case it would create a facilitation effect (Hamburger and Röser, 2014), which does not seem to be the case for olfactory information. Consistent with the assumption, Hamburger and Röser (2011) found no switching costs between auditory and visual landmark information. It is possible that neither odors nor images are initially processed in the other modality, which could explain the poorer performance of the participants in the “switch” condition, as it would require additional cognitive effort to transfer the information to the other modality. On the other hand, our findings illustrated in Figure 6 also show that it was easier for the participants to switch from olfactory to visual stimuli than vice versa. This means an advantage for switching from olfactory to visual stimuli since fewer cognitive

effort is required to transfer the olfactory information into the visual modality. In addition to the above explanation, based on these results, it is also possible that odors are initially processed in the visual modality as well (i.e., mental images), but images do not mentally occur in the olfactory modality, which would explain the participants' poorer performance in the "visual to olfactory" switching condition. If this were the case, it would mean an initial double-coding for the first case but a single-coding for the second. Thus, additional cognitive resources would only be required when the visual needs to be transferred to the olfactory modality during information retrieval.

Overall, it can be concluded that humans are able to orient themselves even when switching between visual and olfactory landmark information, but their performance decreases compared to a switch between visual and auditory information.

In addition to a lower relative number of correct decisions, decision times were higher in the "switch" condition than in the "no-switch" condition, which is consistent with the hypothesis about switching costs, i.e., decision times. Although, the decision times of olfactory stimuli should not be overestimated due to ambiguous findings. Since literature shows that response times for the olfactory system are significantly longer than for visual stimuli (Cain, 1976; Spence et al., 2000), this could also explain the differences in response time that we report. On the one hand, according to Radil and Wysocki (1998), the sense of smell is a diffuse sense, which is why an exact localization of olfactory stimuli proves to be difficult. On the other hand, Porter et al. (2007) also investigated the sense of smell in humans and the ability to scent-track based on odors. According to them, humans are able to follow olfactory traces and even improve with practice.

5.5.1 Limitations

It is unclear whether the presentation of olfactory stimuli also triggers increased activation in visual cortex as described above, as is the case with auditory stimuli. To investigate this further, imaging techniques would have to be utilized after the application of odors. It could then be clarified whether olfactory information is initially also processed in the visual or another modality. This could provide further insight into landmark-based wayfinding as well.

Another explanation could also be of a methodological nature. The odors presented to the participants as landmark information were presented by hand, which is the reason why no standardized

presentation of the stimuli was possible. Since the focus was on the investigation of switching costs, this did not pose a problem in answering the question to be examined. However, Jacobs (2012) showed that an unequal distance of the odors to the nose results in a different intensity, which may affect the performance and decision times of the experimental participants. Therefore, for future research and especially for a time-accurate interpretation of odors, it would be useful to utilize devices that allow a standardized presentation of odors. This could be circumvented by using an olfactometer, which is capable of rapidly delivering discrete odor stimuli without tactile, thermal, or auditory variations (Gottfried et al., 2002), and which would allow a more valid interpretation of the decision times. Moreover, the presentation of odors by hand while seeing an empty intersection on screen limits the ecological validity. Since this study serves primarily as fundamental research, the focus here was on whether navigation with a modality switch is possible. Future studies, i.e., application studies, should use a more realistic implementation of the odor cues, for example by doing an open-field study where the olfactory landmark cues would be located along a real-world route.

In general, participants in all stages in which odors were included showed poorer performance compared to the participants in the condition in which only visual stimuli were tested (“no-switch”). However, it must be emphasized that this is only due to the increased difficulty of using olfactory cues in visual environments compared to using visual cues and not due to a general inability of humans to orient and navigate using olfactory landmark information, as evidenced by several studies mentioned above (e.g., Jacobs et al., 2015; Hamburger and Knauff, 2019).

In addition to the already mentioned higher initial processing times of olfactory than for visual inputs (Cain, 1976; Spence et al., 2000), the emotionality of the participants could possibly provide an explanation. Emotions generally have an influence in wayfinding as well, as demonstrated by Palmiero and Piccardi (2017). In this study participants who saw visual emotional landmark information showed better orientation performance than participants who saw neutral emotional landmarks, which is in line with the results of Balaban et al. (2017). Accordingly, an emotional association appears to have an impact on wayfinding performance when visual landmark information is presented, but whether this is also the case for olfactory landmark information is unclear. Moreover, Bestgen et al. (2015) showed that

the emotional quality of odors predicts odor identification. However, it is yet unclear, whether odor quality might have an impact on (spatial) memory performance and therefore human wayfinding as well.

It is equally possible that the Proust effect (e.g., Van Campen, 2014) applies to olfactory landmark information. This effect occurs when odors induce episodic memories. Here, odors evoke different memories and could thus lead not only to a higher load on the cognitive system (i.e., working memory) but also to a distraction from the actual wayfinding task. Accordingly, this could likely cause longer decision times. This would mean that if a certain odor were to induce a specific memory from the past, the working memory would be under more load and an additional cognitive effort would be the result. On the one hand, the load on working memory could lead to a greater depth of processing, but on the other hand, triggered memories could also provide distraction and thus poorer performance (e.g., attention), which the results tend to suggest. Thus, the research interest extends to landmark-based wayfinding of olfactory cues with an emotional component. Specifically, we could investigate whether a specific emotional meaning of the stimuli, i.e., positive, negative, or neutral, leads to differences in orientation performance.

Closely related to this is also the salience of odors. Caduff and Timpf (2008) focused on the concept of saliency, which refers to relatively distinct, salient, or obvious features compared to other features. Visual salience dominates visual attention during indoor wayfinding (Dong et al., 2020). It is questionable whether the salience of olfactory information also influences participants' wayfinding.

5.5.2 Conclusion

With this study, we demonstrated that a modality switch between visual and olfactory landmark information has a significant impact on wayfinding. For this reason, we again underline the necessity to consider different approaches to study the role of the different modalities in landmark-based wayfinding, in order to achieve a more comprehensive understanding of the underlying cognitive processes in human spatial orientation.

5.6 Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

5.7 Ethics Statement

The studies involving human participants were reviewed and approved by FB06, JLU Giessen; 2014-0017. The participants provided their written informed consent to participate in this study.

5.8 Author Contributions

KH contributed to conception and design of the study and organized the database. KH and MS performed the statistical analysis. MS wrote all sections of the manuscript. All authors contributed to the article and approved the submitted version.

5.9 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

5.10 Publisher's Note

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⁴ In this dissertation, references are presented in the same format as they appeared in the journals in which the respective articles were published. They have not been adjusted to APA 7 style in order to preserve the original published format.

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6. Implicit versus Explicit Processing of Visual, Olfactory, and Multimodal Landmark Information in Human Wayfinding⁵

6.1 Abstract

Despite the predominant focus on visual perception in most studies, the role of humans' sense of smell in navigation has often been neglected. Recent research, however, could show that humans are indeed able to use their sense of smell for orientation, particularly when processed implicitly. In this study, we investigate whether implicit perception of olfactory landmarks enhanced wayfinding performance compared to explicit perception. Fifty-two people completed a wayfinding and a recognition task in a virtual maze at two times of testing 1 month apart. Participants either received olfactory, visual, or both cues at the intersections. Wayfinding performance was better for olfactory landmarks, which were not correctly remembered in the recognition task. In contrast, wayfinding performance was better when visual landmarks were correctly remembered. In the multimodal condition, wayfinding performance was better with landmarks being remembered at t1 and remained the same at t2. Our results suggest distinct implicit processing mechanisms within the olfactory system and therefore hold important implications for the nature of spatial odor processing extending beyond explicit odor localization tasks. The study highlights the importance for future studies to develop and employ further experimental methods that capture implicit processing across all of our senses. This is crucial for a comprehensive understanding of consciousness, as olfaction strongly influences our behavior, but remains largely latent unless deliberately honed through practice.

⁵ Schwarz, M., & Hamburger, K. (2023). Implicit versus explicit processing of visual, olfactory, and multimodal landmark information in human wayfinding. *Frontiers in Psychology, 14*, 1285034. <https://doi.org/10.3389/fpsyg.2023.1285034>

6.2 Introduction

The use of odors to influence human behavior is widespread in practices like aromatherapies (Tisserand and Balacs, 1996) and marketing (Emsenhuber, 2009). The impact of olfactory information on our behavior is commonly accepted in society (Degel and Köster, 1999). Nevertheless, to date there has been limited research studying this influence, as research has long credited the human olfactory system with only its classical functions for self-preservation [finding food (Yeomans, 2006) or perceiving warning signals (Scherer and Quast, 2001)]. For a long time, humans were even considered anosmatic, as suggested by Broca (1879). Looking back, this wasn't due to their lack of olfactory abilities, but rather their inability to consciously select a response to an olfactory stimulus (McGann, 2017). However, over time, distinct features of human olfaction were discovered that distinguish it from all other senses. With its uniqueness, the sense of smell thus represents a meaningful approach for future research into fundamental human brain processes.

One of the outstanding features of the human olfactory system is its close connection to our emotions (Aggleton and Mishkin, 1986). This connection, which was initially based only on introspection and observation, received tremendous support from brain imaging studies (Aggleton and Mishkin, 1986; Herz, 1998; Herz et al., 2004); and could potentially explain why the sense of smell plays a fundamental role in shaping our behavior, given that emotions have a pervasive influence on virtually every aspect of cognition (Tyng et al., 2017).

Moreover, the olfactory system exhibits a unique connection with memory (Stäubli et al., 1984; Schwerdtfeger et al., 1990; Cahill et al., 1995; White et al., 2015). In particular, long-term memory displays exceptional resistance to decay, while Herz and Engen (1996) found short-term memory to be relatively weak or even absent. However, since they tested short-term memory only explicitly, its absence could also imply that the odors were not processed explicitly, but rather implicitly. While explicit memory involves conscious recall, as required for example in a vocabulary test; implicit memory is used unconsciously (Buchner and Wippich, 1998). Classic examples for that include riding a bike or reading a book. Both memory systems influence our behavior in everyday life (more or less consciously). While there are many studies on explicit memory, it is difficult to study implicit memory.

Especially implicit olfactory memory remains largely unexplored and has only partly been demonstrated to date (e.g., Schab and Crowder, 2014). However, Degel and Köster's (1998, 1999) pioneering studies on implicit olfactory memory revealed evidence of implicitly learned odor memories. Participants rated odor congruence with visual contexts, showcasing an early systematic exploration of implicit olfactory memory (Degel and Köster, 1998, 1999). Exposure to an odor unknowingly resulted in later association of the odor with its exposure site. Interestingly, this effect manifested when participants could not label the unconsciously perceived odor. Naming the odor could impede implicit memory, indicating that odor naming might negatively impact wayfinding. This finding was also confirmed in a repetition priming experiment with odors by Olsson (1999). He demonstrated that incorrectly identified odors were processed faster than odors that were correctly identified. This finding again provides evidence for a possible interference effect of explicit processing of odors (i.e., knowing the name of an odor) with the establishment, retention, or retrieval of (implicit?) odor memory (see also Degel et al., 2001). Moreover, Moessnang et al. (2011) used a directional smell cueing paradigm, indicating implicit directional smelling ability. Olfactory stimuli congruent with cued targets led to slower responses, highlighting cross-modal attentional interference. The explicit condition performance was at chance-level, showing humans' incapability to consciously determine odor location. Wudarczyk et al. (2016) adopted Moessnang et al.'s (2011) paradigm to investigate implicit and explicit processing differences of olfactory and trigeminal stimuli, supporting an implicit-explicit dissociation of olfactory localization (Wudarczyk et al., 2016).

Besides its distinctive connection to emotions and memory, the sense of smell possesses another unique trait: it phylogenetically stands as the oldest sense, being the initial form of interorganism communication (Hoover, 2010). Looking at the evolution of the vertebrate brain, olfactory bulb size shows unparalleled variability, distinct from other brain regions scaling with brain size (Jacobs, 2012). Although this variability appears to be a consequence of olfactory functions, it remains unexplained within the classical olfactory functions (see above). This finding prompted Jacobs (2012) to propose the olfactory spatial hypothesis, suggesting that the sense of smell originally evolved to support spatial orientation (Dahmani et al., 2018; Jacobs, 2019), thereby significantly influencing perception and navigation (Huber et al., 2022). If navigation underpins olfaction's primary role (i.e., predicting odorant

distributions in time and space) – instead of self-preservation in terms of finding food or perceiving warning signals - olfactory bulb size variation effectively reflects the navigational demands of different vertebrate species (Jacobs, 2012). Following this hypothesis, new discoveries caused many of our preconceived notions about the contribution of olfaction to spatial representations to be challenged (Jacobs, 2022).

In contrast to prior beliefs, where navigation was primarily viewed as a visual process and research largely focused on unimodal visual wayfinding, the olfactory spatial hypothesis promoted experiments demonstrating that humans are also able to navigate through (virtual) environments based on their sense of smell alone (Jacobs et al., 2015; Hamburger and Knauff, 2019; Schwarz and Hamburger, 2022). Remarkably, wayfinding performance did not differ between different modalities (i.e., auditory, visual, verbal, olfactory; Hamburger and Röser, 2014; Arena and Hamburger, 2023). In these experiments, so-called landmarks were used as orientation reference. The existing literature defines landmarks as distinct objects or location in an environment that serves to define the location (Hirtle, 2008). Even though, it seems intuitively plausible that mainly visual landmarks are incorporated for the construction of cognitive maps, we propose a multimodal representation of cognitive maps in which our senses work together rather than acting as separate entities (Karimpur and Hamburger, 2016; Hamburger and Knauff, 2019; Arena and Hamburger, 2022; Schwarz and Hamburger, 2022). Despite a widespread acceptance of multimodal sensory processing (e.g., Spence, 2020), research mainly remains unimodal for human navigation. We believe that to comprehensively understand human cognition, we urge to shift from a unimodal perspective to a more realistic multimodal comprehension, especially in the context of spatial cognition.

With regard to olfactory spatial cognition, humans tend to use olfactory landmarks implicitly rather than explicitly in navigation (Moessnang et al., 2011; Wudarczyk et al., 2016). This poses two major issues: studies often omit smell due to exclusive reliance on explicit processing methods, such as recognition tasks only (Abu-Obeid, 1998; Choi et al., 2016); second, data from experiments that capture the implicit olfactory processing cannot yet be explained by existing theories because processing odor stimuli is still poorly understood. However, previous wayfinding studies involving olfactory landmarks already yielded contradictory results regarding performance in recognition and wayfinding tasks. While

recognition outperformed wayfinding across all sensory modalities by around 10% (Hamburger and Röser, 2014; Karimpur and Hamburger, 2016; Arena and Hamburger, 2022), intriguingly, incorrectly recognized olfactory landmarks still facilitated accurate wayfinding decisions (Arena and Hamburger, 2022). This phenomenon was exclusive to olfactory landmarks, implying that recognition is not a prerequisite for effective wayfinding using odors and stands in line with previous findings regarding implicit odor memory (see above). Furthermore, investigations into “switching costs” - the cognitive toll of switching modalities during tasks – indicated no decline in wayfinding performance when alternating between auditory and visual landmarks (Hamburger and Röser, 2011). This aligns with the idea that images and sounds engage the same cognitive system. Conversely, transitioning between olfactory and visual landmarks incurred switching costs and wayfinding performance reduction (Schwarz and Hamburger, 2022), pointing toward distinct cognitive processing for odors and images. An explanation for that could be an implicit use of olfactory landmark information in comparison to an explicit use of visual landmarks. Here, Hamburger (2020) applies the cognitive concept of two processing systems (system 1 for fast, automatic processing and system 2 for conscious, deliberate processing; Kahneman, 2011) to landmark-based wayfinding. In an unfamiliar environment, conscious landmark-use engages System 2, whereas familiar environments likely trigger unconscious, System 1-based processing. We assume, olfactory landmarks likely engage the evolutionary older System 1, given our inability to consciously perceive or name most odors.

In summary, the olfactory system is essential for wayfinding in many mammals (e.g., Steck, 2012) and almost certainly evolved originally in humans to support spatial navigation (e.g., Dahmani et al., 2018; Jacobs, 2019). We are therefore indeed capable of using olfaction for wayfinding (e.g., Hamburger and Knauff, 2019), but it is believed that this is only possible when assessed implicitly (e.g., Moessnang et al., 2011). Due to these numerous peculiarities of the human olfactory system, the sense of smell is an excellent model for investigating implicit, emotional, sensory processing and especially human navigation and orientation processing. Despite the visual sense remaining the most important of all senses in human navigation, we want to focus on a more comprehensive understanding of navigation with all senses. Therefore, this study tests whether implicit processing of olfactory landmark information

leads to better wayfinding performance than explicit processing of olfactory landmarks. We aim to show that olfactory landmarks are not required to be consciously perceived to ensure successful wayfinding.

6.3 Materials and Methods

6.3.1 Participants

Fifty-two people volunteers partook in the experiment at both times of testing, divided pseudo-randomly across three conditions (39 female, 13 male; age: 19–61, $M = 27.27$, $SD = 11.11$; olfactory unimodal: $n = 16$, visual unimodal: $n = 18$, visual \times olfactory multimodal: $n = 18$). As already demonstrated in Hamburger and Röser (2014) no gender differences were found in the current study. All participants had normal olfactory and visual functions, and their written informed consent was obtained, approved by a local ethics committee (Department of Psychology, JLU; 2014-0017) adhering to the Declaration of Helsinki guidelines. Participants received course credits or entered a raffle for ten 20€ Amazon vouchers as compensation.

6.3.2 Material

Data collection comprised three experimental blocks: learning-, wayfinding-and recognition phases (Figure 1). Throughout, participants wore an HTC Vive head-mounted display (HMD) to minimize distractions and ensure equal immersion for all participants. A video showed a path through a self-built 3D virtual maze created with Minecraft® (Mojang Synergies AB, n.d.). The route, shared among all conditions, included 12 directional changes (six right, six left) and passed straight ahead six times at a total of 18 intersections. To counter potential position biases, half the participants viewed the vertically mirrored video, reversing turns systematically. At each intersection, participants encountered an odor, picture, or both (= landmarks).

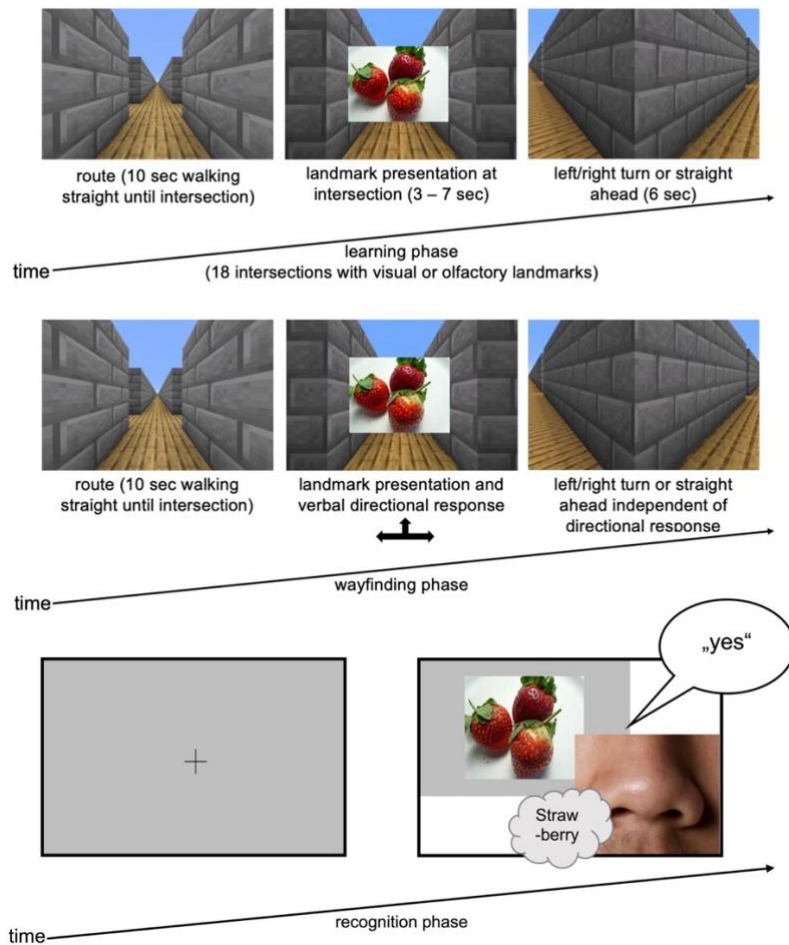
Olfactory landmarks were selected based on an olfactory salience assessment (valence, arousal, dominance) by Hamburger and Herold (2021). We used 36 odors with varying valence, arousal, and dominance. From these, 18 odor pairs of similar valence scores (according to Hamburger and Herold, 2021) were created, with half serving as landmarks. The remaining 18 matched odors were distractors for the recognition task, appearing randomly alongside the 18 landmarks. For visual and multimodal conditions, 36 photos matching the chosen odors (e.g., strawberry scent and strawberry image) were

gathered from private sources and the license-free stock images provider pexels.com. Therefore, half the odors and matching pictures (n = 18) functioned as distractors, while the rest became visual and olfactory landmarks.

A comprehensive list of landmarks and distractors is available in the Supplementary Material.

Figure 1

Experimental procedure



Notes. (left) Exemplary route for the learning phase in a virtual environment built with Minecraft® with either olfactory or visual cues at each intersection (cloud symbol); (top right) in the wayfinding phase participants again saw the video sequence which was stopped at every intersection and they had to decide – based on the specific landmark (olfactory or visual) at the intersection – whether to turn right, left or move straight; (bottom right) in the recognition phase the 18 landmarks plus 18 distractors (olfactory or visual) were presented in random order, participants had to decide whether they already smelled/saw the cues in the learning and wayfinding phase (“yes”/“no”).

6.3.3 Procedure

In the first experimental block, the learning phase, participants watched the video of the route through the virtual maze including 18 landmarks (visual, olfactory or both) at intersection. Their task was to remember the route after a single viewing. Landmarks were presented as pictures at intersection for 3 s (= visual condition; Figure 1) or as hand-administered odors for 7 s (= olfactory condition) since the processing time of odors is longer than for pictures (Cain, 1976; Posner and Cohen, 1984). In the multimodal condition, participants watched the video with visual landmarks while simultaneously receiving matching olfactory landmarks by hand for 7 s. See Figure 1 for further time specifications.

For the wayfinding task, the second experimental phase, the same video was presented. At intersections, the video paused until the participants verbally and or manually by hand signal indicated the route direction (left, right, straight), allowing for possible left–right confusion. Regardless of their response, the video continued into the correct direction. This allowed participants to check whether they answered correctly (i.e., if the route in the video continued in the same direction as they indicated) or if they made a mistake (i.e., if the route continued in a different direction than indicated).

The final experimental block, the recognition task, presented 18 landmarks and 18 distractors in randomized order, using the same modality as in the learning phase. Participants swiftly identified if the presented stimulus was a landmark or distractor, responding verbally with “yes” or “no.” To counter position biases, six randomized stimulus representations were created for the recognition task.

One month later, the second testing (t2) excluded the learning phase, focusing on experimental blocks 2 and 3. Route, stimulus sequence, and modality were consistent with the first testing (t1). After these tasks, participants completed a questionnaire covering demographics, strategy usage, and prior experiences with olfactory and navigation experiments.

Repeated and prolonged presentation of similar odors results in olfactory adaptation, which can cause perceptual decrease (Ferdenzi et al., 2014). With their outstanding, intense smell, coffee beans can have the ability to avoid this olfactory fatigue. Therefore, throughout the experiment, participants in the olfactory and multimodal conditions could pause to reset their olfactory sensitivity by smelling coffee beans, ensuring sustained olfactory discrimination ability (Secundo and Sobel, 2006). A minority of participants used coffee beans to neutralize their sense of smell only during the recognition phase. In

the wayfinding phase, the intervals between landmark presentation at each intersection were long enough (16 s, see Figure 1) to avoid olfactory adaption. Pausing had no effect on recognition performance.

6.4 Results

6.4.1 Data Reconstruction

For interference analyses, we categorized participants' wayfinding performance into explicit and implicit (?) processing groups.

In the experiment, participants recalled directions at intersections for the wayfinding task, while the recognition task explicitly focused on correct landmark recall without linking it to path decisions. Recognition tests are direct memory tests, measuring explicit memory whereas the wayfinding task cannot yet be clearly classified as an implicit or explicit memory test. If a participant correctly identified a landmark in the recognition phase, we inferred that this landmark had been explicitly processed in the previous wayfinding phase and that the participant could therefore identify it in the subsequent recognition phase. This created an explicit processing subgroup, containing wayfinding responses for intersections where participants correctly recognized corresponding landmarks.

However, during the experiment and data review, we noted instances where landmarks were often not correctly recognized in the recognition phase yet still led to accurate wayfinding decision in the preceding wayfinding phase. This was also reflected in the participants' comments during the experiment, as they verbally told the experimenter that they no longer had any memory of the route or landmarks, especially at the second time of testing. Nevertheless, the wayfinding performances were above chance level. This finding is particularly noteworthy considering the chance probabilities of correct responses. The chance of randomly giving a correct answer is 50% in recognition (two options: landmark vs. distractor) and one-third in wayfinding (three options: right, left, straight). It is therefore striking that correct recognition responses by chance were likelier than wayfinding responses.

If a landmark cannot be explicitly recalled in recognition yet, it still leads to accurate wayfinding; reasons could be (1) encoding failure, (2) retrieval failure, (3) pure luck in giving the correct wayfinding response, (4) sequential learning of the route in the wayfinding task, or (5) exclusive implicit

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processing of this landmark. In any previous experiments using the same wayfinding and recognition tasks (e.g., Hamburger and Knauff, 2019), sequential learning, instead of landmark-based learning, was always controlled for. This was tested by additional control conditions such as a task where participants were “beamed” to different intersections where landmarks were again presented without walking the route. Participants then had to verbally indicate the route direction. The wayfinding performance during the beaming phase was equal to the initial wayfinding phase, indicating no sequential learning. If sequential learning had occurred, participants would not have been able to answer correctly in the beaming phase. This approach has already been used frequently in wayfinding studies using similar wayfinding tasks, consistently yielding the same results (Balaban et al., 2014; Hamburger and Röser, 2014; Karimpur and Hamburger, 2016). Moreover, if wayfinding performance was primarily due to sequential learning rather than landmark-based wayfinding, participants would only remember the sequence of directions (i.e., “left,” “right,” “straight,” “left,” ...), with little recollection of the presented landmarks. Consequently, if sequential learning were the dominant factor, recognition performance would be expected to be worse than wayfinding performance, since only the directions could be recalled. However, this is not the case, as recognition performance exceeds wayfinding performance across all three landmark modalities. This was also the case in the previous experiments where we additionally controlled for sequential learning. Nonetheless, it is important to note that sequential learning cannot be entirely ruled out for all participants at all intersections. Hamburger (2020) argues that landmark-based wayfinding in everyday life likely involves a combination of sequential learning and landmark knowledge. Nevertheless, in the present sample, based on the aforementioned reasons, it can be concluded that sequential learning played a minor role, while landmark knowledge was the dominant factor.

Hence, the second subgroup includes wayfinding responses where participants did not correctly recognize landmarks in the recognition phase. For example, if a participant correctly responded directionally for the “strawberry” landmark in wayfinding but incorrectly responded in the subsequent recognition task, implicit processing might have occurred. While the landmark was not explicitly remembered, it still led to accurate wayfinding. Moreover, the second subgroup also contained incorrect wayfinding responses, e.g., when a participant made errors for the landmark “fish” in both the

wayfinding task and the recognition task. In the following paragraphs, the second subgroup is referred to as the “implicit processing” group. However, this expression must be used and interpreted with caution, since we cannot clearly exclude that encoding failure, retrieval failure, pure luck or sequential learning were the reason for recognition difficulties of landmarks. For further information and details, please see Section 4.1.

To clarify our approach, we did not calculate performance comparisons between participants but focused on comparisons between individual landmarks. Therefore, our following analyses use a data set which does not consist of just one data point per participant; instead, it includes 36 data points, corresponding to the 18 landmarks at both times of testing (18×2). For example, within a single participant, 12 landmarks might be categorized as “implicitly processed,” while the remaining 24 are considered “explicitly processed.”

This methodology allowed us to avoid splitting the 52 experimental subjects into numerous subgroups.

6.4.2 Interference Statistics

Data were analyzed using IBM SPSS, version 28.0 (IBM Corp, 2021). For all results, significances, as well as effect sizes are reported. The test assumption of normal distribution tested with Kolmogorov-Smirnov-tests was given for all conditions at all times. Further, Levene tests showed equal variances for most of the conditions. In case of unequal variances Welch’s t-tests are reported. All reported t-tests are for independent samples and are Bonferroni corrected. Wayfinding performance was assessed as percentage of correct route decisions. For this purpose, the number of correct wayfinding decisions was divided by 18 (number of interactions) and multiplied by 100.

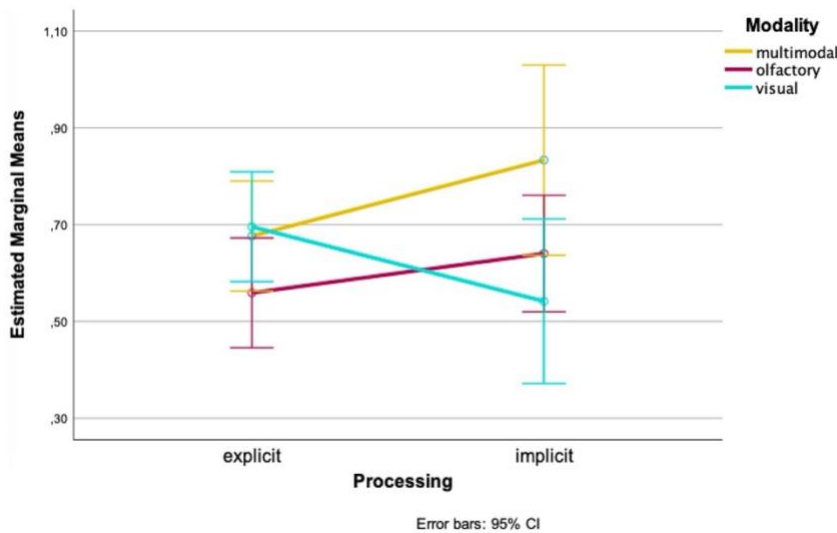
We first calculated a three-way ANOVA with the two between-subject factors “modality” (olfactory, visual, or multimodal) and “processing” (implicit or explicit) and the within-subject factor “time” (first time of testing and second time of testing 1 month later). All interaction effects between the three factors were significant [time \times modality: $F(2, 66) = 15.163, p < 0.001, \eta = 0.315$; time \times processing: $F(1, 66) = 5.673, p = 0.020, \eta = 0.079$; modality \times processing: $F(2, 66) = 10.255, p < 0.001, \eta = 0.237$; time \times modality \times processing: $F(2, 66) = 8.448, p < 0.001, \eta = 0.204$].

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When looking at the mean values of the groups separately, higher wayfinding performances in the olfactory and multimodal conditions were found for implicit processing of landmarks compared to explicit processing at the first time of testing [olfactory: $M_{explicit} = 0.559$, $SD_{explicit} = 0.177$, $M_{implicit} = 0.640$, $SD_{implicit} = 0.274$; $t(32) = -1.039$, $p = 0.153$, $d = 0.228$; 95%-CI (-0.241, 0.078); multimodal: $M_{explicit} = 0.676$, $SD_{explicit} = 0.104$, $M_{implicit} = 0.833$, $SD_{implicit} = 0.408$, $t(5.217) = -0.932$, $p = 0.196$, $d = 0.215$; 95%-CI (-0.585, 0.271); Figure 2]. The visual condition, on the other hand, showed higher values in explicit processing [$M_{explicit} = 0.696$, $SD_{explicit} = 0.084$, $M_{implicit} = 0.542$, $SD_{implicit} = 0.502$, $t(7.173) = 0.862$, $p = 0.208$, $d = 0.280$; 95%-CI (-0.266, 0.574); Figure 2].

Figure 2

Mean wayfinding performance for the first time of testing

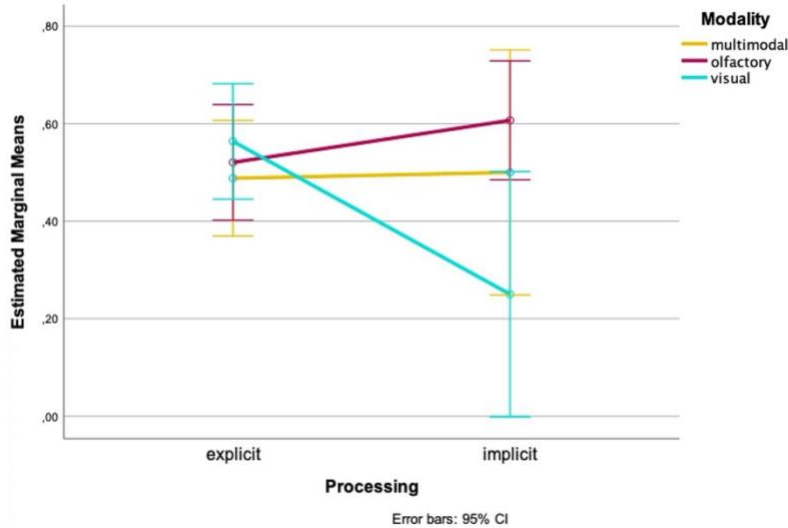


At the second time of testing, the wayfinding performance in the multimodal condition is almost equally good for explicit and implicit processing [$M_{explicit} = 0.488$, $SD_{explicit} = 0.157$, $M_{implicit} = 0.500$, $SD_{implicit} = 0.577$, $t(3.099) = -0.041$, $p = 0.485$, $d = 0.266$; 95%-CI (-0.922, 0.898); Figure 3]. Once again, at the second time of testing wayfinding performance of the olfactory condition is higher for implicit processing [$M_{explicit} = 0.521$, $SD_{explicit} = 0.191$, $M_{implicit} = 0.607$, $SD_{implicit} = 0.301$; $t(33) = -1.020$, $p = 0.158$, $d = 0.250$; 95%-CI (-0.259, 0.086); Figure 3]. In the visual condition wayfinding performance was higher when processing explicitly at the second time of testing [$M_{explicit} = 0.564$, $SD_{explicit} = 0.168$,

$M_{implicit} = 0.533$, $SD_{implicit} = 0.388$, $t(3,130) = 1.242$, $p = 0.150$, $d = 0.241$; 95%-CI (-0.472, 1.100); Figure 3].

Figure 3

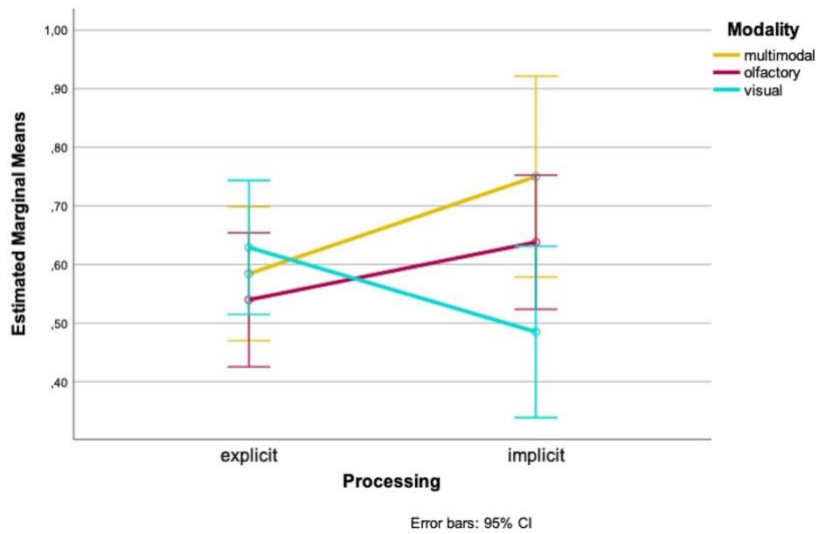
Mean wayfinding performance for the second time of testing



In further analyses, we looked at the data from both times of testing combined. A two-factor ANOVA with the between-subject factors “modality” and “processing” revealed a marginally non-significant interaction of both conditions [$F(2, 85) = 2.936$, $p = 0.059$, $\eta = 0.065$]. Looking at the mean values of the groups separately, higher wayfinding performances in the olfactory and multimodal conditions were found for implicit processing of landmarks compared to explicit processing [olfactory: $M_{explicit} = 0.540$, $SD_{explicit} = 0.161$, $M_{implicit} = 0.638$, $SD_{implicit} = 0.202$; $t(34) = -1.617$, $p = 0.058$, $d = 0.182$; 96%-CI (-0.222, 0.025); multimodal: $M_{explicit} = 0.584$, $SD_{explicit} = 0.116$, $M_{implicit} = 0.750$, $SD_{implicit} = 0.378$, $t(7,595) = -1.215$, $p = 0.130$, $d = 0.226$; 95%-CI (-0.483, 0.152); Figure 4]. Looking at the visual condition, an opposite effect was found: wayfinding performance was higher when landmarks were processed explicitly whereas it was lower when they were processed implicitly [$M_{explicit} = 0.629$, $SD_{explicit} = 0.102$, $M_{implicit} = 0.485$, $SD_{implicit} = 0.503$, $t(10,511) = 0.940$, $p = 0.184$, $d = 0.316$; 95%-CI (-0.195, 0.484); Figure 4].

Figure 4

Mean wayfinding performance for both times of testing



6.5 Discussion

The question of whether and how humans are also able to orient themselves using their sense of smell has long been neglected in research on spatial thinking. The present study aimed to contribute to this field of research by investigating the implicit spatial processing of two sensory systems and its interaction. By using a recognition and wayfinding task to assess explicit and implicit processing of visual, olfactory and multimodal (visual \times olfactory) cues, our results point to a facilitation of wayfinding performance by implicit processing of olfactory cues.

Our analyses show interaction effects of the variables “time of testing,” “processing” and “modality.” When looking at the means, wayfinding performance was better for olfactory landmarks, which were not correctly remembered in the recognition task compared to when correctly remembered. In contrast, wayfinding performance was better when visual landmarks were correctly remembered compared to when not correctly remembered. In the multimodal condition, at the first time of testing, wayfinding performance was better with landmarks being remembered; at the second time of testing wayfinding performance remained almost the same. However, all pairwise comparisons did not become significant.

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With that, the present study is the first to differentiate between implicit and explicit processing of the participants' wayfinding performance. And, it reveals a finding consistent with our hypothesis of implicit processing: People seem to be very good in navigating when using olfactory stimuli as landmarks without explicitly memorizing them in a subsequent recognition task, whereas visual landmarks are mainly used explicitly. Outside the laboratory setting, people are likely to use all modalities available to them implicitly or explicitly (depending on the modality). Here, it seems as if the wayfinding performance in the multimodal condition could be derived additively from olfactory and visual performance since visual performance is worse with implicit processing, but wayfinding performance is better with implicit olfactory processing. Especially at the second time of testing, these two opposite effects of the unimodal conditions seem to balance out in the multimodal condition, as wayfinding performance remains the same for implicit and explicit processing.

We assume that the ability to navigate through the virtual maze relies on short-term memory at the first time of testing whereas at the second time of testing the wayfinding task must be solved using long-term memory. According to previous studies, there seems to be hardly any or even no (explicit) short-term memory for odors (Herz and Engen, 1996). Therefore, explicit performance in the multimodal condition must rely mainly on visual information, which is shown by the almost equal performance of the visual and multimodal explicit condition at first time of testing (while the olfactory explicit performance is worse). Apparently, when implicit processing is involved in the multimodal condition, both implicit olfactory and visual information is available to the participants, which could additively lead to a better performance in the multimodal condition than in the two unimodal conditions. Odor long-term memory is reported to be extraordinarily robust to decay (Herz and Engen, 1996). This finding is reflected in our data: Although explicit visual performance was much higher at the first time of testing, participants achieve nearly equal explicit performance in all three modalities at the second time of testing. Both, explicitly and implicitly processed odors lead to almost equal performances after 1 month whereas implicitly processed visual landmarks seem to be no longer represented in long-term memory as performance is below chance level (one third). In the multimodal condition, the landmark information of the long-term odor memory seems to be able to compensate for the loss of the implicitly processed visual information. Thus, in a real environment consisting of multimodal stimuli, we manage

to achieve the best possible performance in wayfinding both explicitly and implicitly by relying on all our senses.

Furthermore, the present study as well as previous studies demonstrate the ability of humans to orient themselves using olfaction (wayfinding performance above chance level; e.g., Porter et al., 2007; Hamburger and Knauff, 2019). However, consciously we rely on the visual–auditory spatial frame for orientation. After all, even though we possess a rather well-established sense of smell, we trust our nose the least of all sensory modalities (Classen et al., 1994; Lundström et al., 2008). In general, humans not only do not report using their sense of smell for orientation, but also lack confidence in their ability to use it (Koutsoklenis and Papadopoulos, 2011; Hamburger and Knauff, 2019). This is because - while our threshold for detecting odorants is very low (e.g., Cain, 1977; Porter et al., 1983; Nagata and Yoshio, 2003) – we are only aware of unusually high odor concentrations (e.g., Lorig, 1992). However, studies have shown that humans can switch from implicit to explicit odor processing in navigation through practice, as seen in lateralization tests (Negoias et al., 2013) and scent tracking (Porter et al., 2007). Thus, it appears that our capacity for olfactory spatial processing is still intact, but it typically operates unconsciously and can be harnessed explicitly with training (Wudarczyk et al., 2016). Based on our findings and existing research, we therefore believe that the main reason for not considering the sense of smell in orientation is its largely unconscious nature and not that it is useless for human orientation.

6.5.1. Limitations and Implications for Future Research

Although all interactions of the three-way ANOVA became significant, none of the pairwise comparisons were significant. In addition, with the experimental design at hand, it will never be possible to prove whether a landmark was processed implicitly but still led to a wrong route decision, since it can also be a mere failure in performance without the landmark having been processed at all (neither implicitly nor explicitly).

For this reason, the study provides only initial evidence. To gain a better understanding, it requires much more sophisticated designs, which we are currently working on for future studies. Nevertheless, we consider the study to be particularly relevant because it has already been able to replicate findings previously found in studies of implicit olfactory memory without a complex experimental design (Moessnang et al., 2011; Wudarczyk et al., 2016). It supports our stated hypothesis

and the olfactory spatial hypothesis that a consistent pattern emerges in the few available studies with a wide variety of experimental designs (Moessnang et al., 2011; Wudarczyk et al., 2016). If a simple, commonly used design like this can replicate the data, we look forward with great confidence to the results of future research in this area.

Future studies could search online databases for further experiments using recognition and wayfinding tasks to perform analogous computations with already existing data sets in wayfinding research. The data from, e.g., Hamburger and Röser (2014) or Arena and Hamburger (2022) are suitable for re-evaluation to explore the differences between implicit and explicit processing of the auditory and olfactory sense in wayfinding. It is not always necessary to conduct new, expensive experiments to explore a new question.

Based on our data we can only suggest that the performance achieved by the participants is due to short-and long-term memory effects, different mechanisms of implicit and explicit processing between distinct modalities, and compensation of weaknesses of one modality by strengths of the other modality. However, these differences need to be further studied in the future.

6.6 Conclusion

The results suggest distinct implicit processing mechanisms within different sensory systems. The best wayfinding performance could be achieved by implicit processing of olfactory stimuli and explicit processing of visual stimuli. It supports and extends the findings of Moessnang et al. (2011) and Wudarczyk et al. (2016) on the existence of an implicit-explicit dissociation of olfactory localization. Finally, the results could lead to new insights and a better understanding of consciousness, as olfaction strongly influences our behavior, but remains largely latent unless deliberately honed through practice. With our study, we highlight the need for future studies to invent and use further experimental methods that capture implicit memory and processing from all of our sensory systems.

6.7 Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

6.8 Ethics Statement

The studies involving humans were approved by local ethics committee of the Department of Psychology (06), Justus Liebig University Giessen. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

6.9 Author Contributions

MS: Writing – original draft. KH: Writing – review & editing.

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6.11 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

6.12 Publisher's Note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

6.13 Supplementary Material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1285034/full#supplementary-material> and in the supplemental material section of this doctoral thesis (page 74).

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6.15 Supplementary Material

Visual and Olfactory Landmarks and Distractors and Corresponding Example Pictures

The visual landmarks were taken from private sources and the license free stock images provider pexels.com.

Landmarks: Fish, Salami pizza, Nail polish, Alcohol, Pineapple, Gras, Aniseed, Fresh Laundry, Eucalyptus
Pepper, Curry, Citron, Vanilla, Aftershave, Tangerine, Strawberry, Basil, Cocoa



Distractors: Garlic, Vinegar, Leather, Spruce needle, Peanut, Frankincense, Coke, Lavender, Melon, Clove,
Peppermint, Coconut, Banana, Apple, Rose, Cinnamon, Licorice, Black Tea



7. The Human Sense of Smell in Spatial Orientation:

A State-of-the-Art Review⁶⁷

7.1 Abstract

An old misconception led to the belief that humans have a poor sense of smell. The sense of smell is a rather primitive but important sense that our ancestors used for hunting, mating, and survival. Throughout the past decades and even centuries, the importance of this sense for our daily lives has been lost under the assumption that “humans have a bad sense of smell.” Especially in combination with spatial orientation and navigation, the sense of smell is of particular importance in a lot of our close relatives in the animal kingdom. Research on humans reveals an immense gap here compared to research on non-human animals. However, there are some findings that suggest that olfaction is also important in human navigation: Olfactory cues are more emotional-laden and memorable than visual cues and it is evolutionary only logical that humans, similar to their close relatives from the animal kingdom, use their sense of smell for orientation as well. Therefore, it is very likely that humans, similar to other animals, use their olfactory system for navigation. The main difference is that humans are not consciously aware of it. As we outline in this review, several findings may explain why olfactory navigation in humans is primarily an implicit process and why it has mainly been neglected in the past. We further give suggestions for future research and how findings in olfactory human navigation can be used for other field outside wayfinding, such as aromatherapy or Alzheimer’s diagnosis.

⁶ Schwarz, M., Yang, A. L., & Hamburger, K. (2025). The human sense of smell in spatial orientation: A state-of-the-art review. *Psychology of Consciousness: Theory, Research, and Practice*, 12(2), 169-185. <https://doi.org/10.1037/cns0000395>

⁷ Please note the following concerning this review: According to Grant and Booth (2009) we aimed for the state-of-the-art review here. We think that this type of review is the most appropriate one since it addresses “[...] more current matters in contrast to the combined retrospective and current approaches of the ‘literature review.’ The review may offer new perspectives on an issue or highlight an area in need for future research” (Grant & Booth, 2009; p. 101). We aim precisely for this in our work concerning the topic ‘the human sense of smell in spatial orientation.’ Due to the nature of this review form, we also decided to not undertake any type of meta-analysis, since to the best of our knowledge the current research would currently not allow for any valuable analyses in this research field. Therefore, we aimed towards relevant content on the topic rather than data quality, research methods applied or the like.

7.2 Introduction

The purpose of this state-of-the-art review is to 1) demonstrate the importance of the sense of smell for human orientation and spatial navigation and 2) to provide suggestions on how it can be systematically integrated into research as well as in everyday life.

The ground is rich in odors. However, since humans started walking upright, our nose is no longer directly near the odor-rich soil. Thus, in the course of evolution, the navigational function of the human nose must have changed with the upright gait. So far, there is some research on the human sense of smell, but it is still underestimated and often neglected in *spatial cognition* research due to flawed prior assumptions. We here address the myth that humans have a poor sense of smell and present studies showing that human olfaction is much better than previously assumed, and that we are very well able to orient ourselves in our environment through the use of olfactory cues – just like our close relatives in the animal kingdom. Therefore, the review aims to offer an overview of what we already know about the sense of smell in human orientation and spatial navigation, and to highlight what remains to be investigated.

7.3 Landmark-Based Wayfinding

We use our navigational skills to get to places. These skills guide us through the world (and the virtual world as well). But how do we navigate in our everyday lives, how do we get to work or back home? The keyword is “spatial orientation” (Benton & Tranel, 1993). Two parameters can define spatial orientation: directional heading and location. Humans need to know their spatial orientation in order to get to places, such as when going from home to work, searching the internet for information, climbing a tree, or even when diving into the ocean. Here, our location can be described in relation to fixed points in the world (Mehlman & Taube, 2019). For such processes, humans and animals use *landmarks*. Landmarks are an example of spatial information and play a crucial role in human’s beliefs about the structure of their environment (Montello, 2017). Humans use them to determine where they are, find a particular destination or describe their environment (e.g., Hamburger & Knauff, 2019). However, the term landmark is not (yet) clearly defined in cognitive sciences (for a brief and critical review see Montello, 2017). They form cognitive anchors or reference points for our daily orientation and

wayfinding (Richter & Winter, 2014; Raubal & Winter, 2002) and usually represent natural objects, such as mountains or manufactured objects, like buildings or pillars (Jellinger, 2000; Lynch, 1960). Definitions generally focus mostly on visual features and how these objects stand out from the environment (e.g., Lynch, 1960; Presson & Montello, 1988; Sorrows & Hirtle, 1999; Hamburger & Röser, 2014; Karimpur & Hamburger, 2016; Epstein et al., 2017; Ekstrom et al., 2018). According to Hutmacher (2019), vision is, undoubtedly, our most important and most complex sense but at the same time the one that is best investigated. However, landmarks and wayfinding/navigation are not limited to the visual cognitive system, as we can see in visually impaired people. They make use of auditory and olfactory sensory information in order to find their way (e.g., Koutsoklenis & Papadopoulos, 2011a, b). Caduff and Timpf (2008) were the first to suggest that auditory and olfactory information should also be included in the world of landmark-based wayfinding for non-impaired, healthy humans. Accordingly, stimuli aiding human navigation might be multimodal in nature, serving as either *landmarks*, indicating direction and distance to a navigational goal or *beacons*, representing the goal itself (e.g., when navigating to a flower shop, the shop, the scent of flowers, and the sound of the doorbell of the flower shop can all function as beacons; Brodbeck, 2012).⁸

7.4 Olfactory Cues for Navigation

Research has in the meantime shown that auditory landmark information can be just as useful for spatial orientation as visual information (Hamburger & Röser, 2014; Karimpur & Hamburger, 2016). However, olfactory information is common in combination with spatial perception (e.g., Vilaplana & Yamanaka, 2015), but rarely combined with spatial orientation (e.g., Gottfried & Dolan, 2003). Therefore, the question remains whether humans use olfactory information as landmark-like information for spatial orientation in everyday life, and if so, how?

Intuitively, the majority of people would answer this question with a clear “no” and without any doubt. We give directions based on visual features such as “Turn left at the white church”. In

⁸ In the present review, we focus on landmarks. However, due to the vague definition of landmarks, we refer to landmarks of any modality with the term “landmark information” or use both terms synonymously.

comparison, we would never think of including odors in such route descriptions (“Turn right at the smell of lavender”).

However, the use of olfactory cues for spatial orientation is evident even in infants, who locate their mothers’ nipples based on scent when visual cues are not yet available (Varendi et al., 1994). Moreover, research has shown that humans can utilize olfactory landmark information for navigation in laboratory settings (e.g., Hamburger & Knauff, 2019).

As these and many other theoretical assumptions and empirical research suggests that olfactory stimuli may also be used in human wayfinding, in the following, we will discuss these arguments and demonstrate why the utilization of scent-based landmarks and beacons is both reasonable and viable for humans, too.

7.4.1 Evolutionary Basis

In order to provide a more thorough and complete comprehension, we will first take a step back and reflect on the evolutionary development of the sense of smell and its function throughout history. From an evolutionary perspective, there also seems to be evidence suggesting a special status of the human sense of smell in spatial orientation. Olfaction is an evolutionary old sense. Its precursors can be found in almost all primitive single-celled organisms to sense its chemical milieu. During evolution, it seems to have evolved further. Our ancestors used their nose primarily for survival (i.e., mating and hunting). However, for several centuries, even millennia, the importance of our sense of smell for survival has faded, thus changing its function. To look at this in more detail, we need to take a brief look at the history of smell and how it fell out of the focus of research.

Non-human animals rely on olfactory, visual, idiothetic, and magnetic cues for navigational processes (Freas et al., 2019). Moreover, numerous studies have already demonstrated the relevance of olfactory cues in the navigation of non-mammalian species (for a review, refer to Baker et al., 2018). But also studies on mammals show that they use the olfactory system to detect and differentiate a high number of passing chemicals (Shepherd, 1988) or sense pheromones, which they use for social interactions or mating behavior (Shepherd, 1988) as well as for navigation. In the latter case, mammals and non-mammalian species, exhibit a diverse range of behaviors to support olfactory navigation, including the use of chemotactic and anemotactic strategies, employing beaconing, route following, and

the development of cognitive maps (Raithel & Gottfried, 2021; for an overview see Vickers, 2000). For example, evidence spanning over 70 years, starting with Tolman's seminal work on rats (1948), indicate that mammalian species can engage with the environment by integrating multisensory information into cognitive maps.

While olfactory navigation (behavior) and its mechanisms have been extensively studied in animals, it was long assumed that humans do not possess the ability for olfactory navigation. The origin of the idea that humans have a poor sense of smell can be traced back to the well-known 19th-century French scientist Paul Broca. In addition to his famous discovery of Broca's area, a part of the brain primarily responsible for human language, he also observed that the olfactory bulb is relatively small in humans compared to other animals (McGann, 2017). This work, along with the observation that humans do not exhibit odor-dependent behavior to the same degree as other animals [for an in-depth exploration of ethological comparisons between humans and non-human species, refer to Raithel and Gottfried (2021), as a thorough analysis of the relevant literature exceeds the scope of this review], led him to conclude that humans rely more on complex thoughts than on low-level olfactory stimuli (i.e., olfactory stimuli at low-intensity levels). He divided mammals into two categories: osmatic animals and anosmatic animals. Osmatic animals, he believed, use their olfactory system as their primary sense, whereas anosmatic animals do not. Based on his findings, he classified humans as anosmatic. William Turner modified this olfactory categorization and divided anosmatic mammals into "microsmatic" and "anosmatic", where "microsmatic" referred to mammals whose olfactory system is weak (Turner, 1890). Neither Turner nor Broca, however, thought to conduct sensory studies. Over the past decades, the above assumptions survived to the present day. Even olfactory experts sometimes seem to get misled by the belief of human olfactory limitations.

The assumption of the regression of our sense of smell was later thought to be rooted in the shift to upright walking, as mentioned in *1. Introduction*. This prevented humans from utilizing the scent-rich ground, which was presumed to be a prerequisite for an acute sense of smell (Titchener, 1915; Sarafoleanu et al., 2009). However, this hypothesis lacks complete satisfaction, given that odors can be transmitted through the air and are, for example, utilized for navigation by flying insects and birds. Here, Papi and colleagues (1972) proposed the "olfactory navigation hypothesis" in pigeons. This hypothesis

assumes that pigeons in their home area can learn windborne environmental odors associated with wind direction. After these odors have been processed, pigeons can recognize the prevalent local odors and recall from which direction they come to find their way back home. Such findings were confirmed in both homing pigeons and other birds (Abolaffio et al., 2018; Bonadonna & Gagliardo, 2021).

Later, Jacobs (2012) proposed the *olfactory navigation hypothesis* in humans since studies emphasize an extraordinary level of variation in the olfactory bulb given the evolution of the vertebrate brain unlike other brain regions which increase proportionally with brain size (Jacobs, 2012). While this variation is thought to be linked to olfactory functions, it cannot be accounted for by the currently accepted classical functions of olfaction (as stated in *1. Introduction*). However, if we consider that the primary role of olfaction is navigation, involving the prediction of odorant distributions in time and space, then the differences in the size of the olfactory bulb could be explained by variations in the navigational requirements of different vertebrate species, including mammals, birds, reptiles, fish, and arthropods.

Dahmani et al. (2018, 2020) examined and validated this hypothesis through a series of studies, discovering positive correlations between spatial navigation performance and olfactory abilities. Particularly, in humans, spatial memory and olfactory identification could be predicted by measures of cortical thickness in the medial orbitofrontal cortex, a region closely associated with higher-order olfactory processing (Dahmani et al., 2018). Consequently, the authors proposed that not only do spatial memory and olfactory abilities exhibit behavioral correlations, but they may also share neural substrates.

Furthermore, there is supporting evidence for olfactory lateralization, as several studies indicate functional asymmetry in olfactory navigation tasks favoring the right nostril and left piriform cortex in homing pigeons (Gagliardo et al., 2005, 2011). In humans, recent studies have uncovered olfactory lateralization and even grid-like codes: Dikeçligil et al. (2023) demonstrated distinct stimuli arising from the two nostrils in the piriform cortex without integration; Bao et al. (2019) illustrated grid-like representations in fMRI responses in the entorhinal cortex and ventromedial prefrontal cortex during navigation, scaled with behavioral performance across participants. Raithel et al. (2023) identified grid-like responses in fMRI data collected during an olfactory navigation task in the entorhinal and piriform cortices, attuned to the same grid orientation. These studies suggest the existence of a distinct and

specialized olfactory grid network capable of processing odor information across nostrils within a single inhalation. These and other findings (e.g., Jacobs, 2015) imply the presence of spatially navigable *olfactory cognitive maps* responsible for guiding spatial navigation using odor landmarks, representing a notable advancement in anatomical analyses of olfactory spatial orientation. Until then, research on cognitive maps in humans had predominantly concentrated on visual perception and the integration of visual landmarks.

However, a key difference between olfactory cognitive maps/navigational stimuli and the perception of visual spatial features is our inability to perceive odors as distinct spatial entities within the environment (e.g., Batty, 2015; Keller, 2017). As Young (2019, p. 151) summarizes, this limitation stems from our inability to define the spatiotemporal boundaries and fixed spatial coordinates of smells. Instead, we perceive smells as odor plumes that partially overlap and disperse in our surroundings (Young, 2019). Young (2020) explains that our olfactory experiences involve odors within a *smellscape* rather than being “object-directed”. The term “smellscape” was introduced by Porteous (1985) and has historical roots, e.g., in the works of Plato and Aristotle, as well as discussions in Indian philosophy (Young, 2019). In summary, in olfactory philosophy *smellscape* describes the olfactory environment as perceived by an individual.

To apply this distinction between object-directed visual landmarks and gradient odors within a *smellscape* to the concept of the cognitive map, Jacobs and Schenk (2003) propose the existence of two parallel cognitive maps: the bearing map and the sketch map. The bearing map is primarily constructed in the dentate gyrus, and is suggested to be a low-resolution grid map, relying on directional cues such as odor gradients; while the sketch map is constructed within the hippocampus, being a high-resolution map, using positional cues, such as visual landmarks (Jacobs, 2015).

In general, it is crucial to note that drawing direct analogies between olfaction and vision should be approached with caution, as emphasized by Young (2019) and Møller and Köster (2023). They highlight the distinct nature of olfactory processing compared to other senses, citing factors such as the need to change position to locate odorants in space, unlike vision, which allows a brief glance to identify all non-hidden objects, even at a distance. All in all, human olfaction possesses several peculiarities that can also be viewed as advantages over the visual system in human navigation processes, notably its

close association with long-term memory, emotions and its unconscious nature, aspects which will be discussed in the following sections. However, in comparison to desert ants, pigeons, or dogs, the human olfactory system is still less sophisticated, but this does not necessarily mean that it may not be (as) functional.

7.4.2 Memorable

Undoubtedly, memory is a key factor in successful navigation. Reaching a desired destination necessitates the recollection of the acquired route to the goal. Here, odors used as landmarks and beacons in navigational processes may have a significant advantage over other stimuli. Odors allow us to mentally travel back in time, vividly relive specific events from our past (i.e., mental imagery), or evoke memories – memories we use to find our way home, or memories long forgotten. Yet, we believe that our sense of smell is not of great value for everyday life. However, it has already been demonstrated that the rate of forgetting odor representations is relatively slow (e.g., Lawless, 1978; Murphy et al., 1991; Saive et al., 2014) and odor-long-term memory is unusually resistant to decay (Herz & Engen, 1996). Anatomically, this link between odors and memories is reflected by a close connection of only three synapses between the hippocampus, which is involved in associative and spatial memory, and the olfactory nerve (Bird & Burgess, 2008). The neuroanatomical link between olfactory bulb, amygdala, and hippocampus might be key to understanding why odor-evoked memories and odors combined with emotions are so easily and persistently formed.

In order to use odorants as landmarks and beacons in wayfinding, olfactory cues have to be remembered correctly. In a landmark-based wayfinding experiment Schwarz and Hamburger (2023a) were already able to demonstrate an advantage of olfactory landmarks compared to visual landmarks over time, since wayfinding performance did not decrease over a one-month period using olfactory landmarks whereas wayfinding performance decreased in the visual wayfinding condition. Thus, olfactory cues may also be of relevance in the long-term representation of spatial information. In the context of long-term memory, perceptual salience and emotional valence are of importance as well.

7.4.3 Emotional-Laden

To correctly remember and identify a landmark, it must be perceptually salient (having the potential to capture attention), cognitively salient (comprising two components: the level of recognition and idiosyncratic relevance), and contextually salient (affecting perception and cognition by determining the amount of attention that can be allocated; Caduff & Timpf, 2008). An odor is perceptually salient when our olfactory system can detect it consciously or unconsciously (further discussed in section 3.4 *Unconscious*) whereas cognitive salience is influenced by idiosyncratic relevance, indicating "the object's personal importance to the observer" (Caduff & Timpf, 2008; p.257). Here, emotions are of particular importance: to facilitate navigation, landmarks should not only be sensory salient but also emotionally relevant. This increases their overall salience. For example, this can be described as follows:

In front of my house there is a lavender bush (author ALY). In the summer, the wind carries the scent of lavender into my house. I did not know the name of the bush for a long time, but I knew the smell by heart; it evoked a strong feeling of home. Since then, this characteristic smell has represented home and always reminds me of the feeling of "coming home."

This example is also reflected by research: In the context of wayfinding, emotional-laden landmarks (positive or negative) have the potential to enhance the construction of a cognitive map, thus facilitating navigation, especially in situations of cognitive overload (Gartner, 2012). Simply put, the emotional salience of the landmark, rather than the individual's emotional state, can serve as a valuable navigational aid (Palmiero & Piccardi, 2017). While research has shown that the individual's emotional state has an impact on navigational strategies and visuospatial memory (e.g., Palmiero et al., 2015), there is a lack of literature that explores emotional-laden landmark information in the context of human navigation and wayfinding (Gartner, 2012; Palmiero & Piccardi, 2017). Recent studies have demonstrated that valence and arousal of landmarks increase landmark salience as well as performance in navigational memory tasks (Piccardi et al., 2020). Balaban et al. (2017) showed that affective reactions play a significant role in wayfinding. In particular, negatively laden (visual) landmarks led to better human wayfinding and recognition compared to neutral landmarks and negative associations are

better remembered over time (here, one week). Furthermore, emotional-laden landmarks improve egocentric-based topographical memory, with positive emotional-laden landmarks being more effective for allocentric-based topographical memory (Palmiero & Piccardi, 2017). Thus, emotions and emotional-laden landmarks, in particular, have a substantial impact on wayfinding, as well as decision making (Damasio et al., 1997), working memory (Gray, 2001), and attention (Montello, 2009).

In the context of olfactory stimuli, Marcel Proust established the hypothesis that odor-evoked memories are more emotional than other sensory memories. The “Proust phenomenon” (Proust, 1919), i.e., the ability of odors to spontaneously evoke vivid autobiographical memories (see, for instance, van Campen, 2014), has been supported by many research studies. As described in the example above by author ALY, memories are more emotional, positive, and detailed when represented in their olfactory form than when presented with the same cue in a different sensory modality (Engen et al., 1973; Rubin et al., 1984; Herz & Cupchik, 1992; Herz, 1998; Chu & Downes, 2000; Herz & Schooler, 2002; Willander & Larsson, 2006; Arshamian et al., 2013).

Anatomical findings also suggest at least a close connection between odors and emotions since the olfactory bulb is separated from the amygdala by only two synapses, and the amygdala is involved in the expression and experience of emotions (Gallagher & Chiba, 1996). The “direct-synapsing hypothesis,” illustrates this immediate connection between the olfactory bulb and the amygdala, which may subserve as emotional connotation in olfactory processing (Herz & Cupchik, 1992; Herz & Schooler, 2002; Herz et al., 2004; Willander & Larsson, 2006, 2007). These projections are assumed to provide the basis for learning, memory, and emotional association of odors (Nigri et al., 2013). Behavioral data further supported the link between olfaction and emotions (Herz, 1998; Herz et al., 2004). Regarding navigation, there are no studies known to the authors that investigate the influence of emotions on olfactory-based wayfinding. However, since emotions and odors are so closely linked (Bensafi et al., 2002), it stands to reason that odors are also important for navigational performance but are more likely to be associated with automatic and unconscious processing.

Considering these atypical neuronal and perceptual findings of our olfactory system, odor memory is likely to be distinct from and more resistant to the memory of visual or verbal stimuli and could therefore serve as excellent landmark material. However, even though many arguments and

empirical findings point in its favor, the sense of smell remains underrepresented in human spatial orientation research compared to other modalities, especially vision. A more comprehensive examination of human olfaction, especially concerning its functionality, is crucial to assess its potential role in spatial navigation.

7.4.4 Unconscious

To date, research on olfactory navigation is hampered by the fact that people normally do not consciously use their sense of smell to navigate and cannot articulate its function in wayfinding. One might say, olfactory landmarks' perceptual salience is usually not given. Furthermore, some researchers in the past have been concerned about the reliability of olfactory cues in real-world settings due to wind direction, interference with other odors, and low consistency of odor stimuli (Koutsoklenis & Papadopoulos, 2011a), and have instead emphasized the visual cues that guide human navigation. However, Wallraff and Andreae (2000) refuted this criticism for olfactory information, showing that airborne volatile organic compounds could represent stable spatial gradients in the atmosphere. But the question still remains as to why people mainly perceive olfactory stimuli on a subconscious level, although they have a decisive influence on their actions and decisions?

The most consistently observed and replicable aspect of consciousness is its limited processing capacity (Baddeley, 2007; Kahneman, 1973). Nevertheless, in the last few decades, various disciplines within cognitive science have presented a new perspective on unconscious processes. These processes now appear capable of performing tasks that were previously believed to necessitate conscious awareness (Hassin et al., 2005). According to Hassin (2013), these tasks include complex information processing, behavioral responses, and the pursuit of goals and self-regulation, indicating that unconscious processes can execute the same fundamental, high-level functions as conscious processes. While cognitive control and working memory were traditionally linked to conscious awareness (e.g., Baddeley, 2000), it has been demonstrated that working memory can also operate outside of conscious awareness (Hassin, 2005).

When considering olfaction, its computational and phenomenological simplicity and distinctiveness provide a unique advantage. The most notable distinction between olfaction and other

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senses lies in the content of consciousness, making it an ideal system for testing theories of consciousness (Keller & Young, 2014).

Under certain circumstances (e.g., when all other senses are blocked, e.g., by blindfold) humans are indeed able to use their sense of smell consciously to navigate (Porter et al., 2007). However, the question arises as to whether we actually only use our sense of smell in everyday life when olfactory information is exclusively available to us, as is the case with blind people, for example. Yet, another possibility is that healthy people also use their sense of smell unconsciously (automatically and/or without awareness) in combination with other sensory impressions (i.e., visual, auditory, tactile).

Results of recent studies point to the latter. They show, for example, that odors can only be localized when processed implicitly (Wudarczyk et al., 2016) or that olfactory landmarks lead to better wayfinding performance when not processed explicitly (Schwarz & Hamburger, 2023b). These findings indicate that perceptual salience in odors does not necessarily have to occur on a conscious level of perception. Thus, one reason that the olfactory system is underestimated (and rarely studied) in relation to wayfinding may be due to the mostly unconscious use of the sense of smell (Hamburger & Herold, 2021). Even though humans are capable of discriminating up to 1 trillion olfactory stimuli (Bushdid et al., 2014), even at low concentrations. This makes the olfactory system much more sensitive than our visual or auditory systems (Crocker & Henderson, 1927; Bushdid et al., 2014). However, olfactory research employs methodologies from visual perception studies that are not fully equipped to comprehensively capture odor perception (Møller & Köster, 2023). For example, the unconscious nature of the human olfactory sense is evident in the challenges associated with verbalizing olfactory experiences (Wippich et al., 1989), making it hard to identify/label specific odorants and their components. Furthermore, natural olfactory stimuli typically consist of a mixture of a large number of diverse components in varying ratios, which makes it difficult to estimate the dimension of odor space. The bias towards vision regarding human navigation might therefore not just be due to a worse human olfactory system compared to animals but also due to identification and naming problems (i.e., in vision, we say “this is...” while for auditory and olfactory information, we tend to say “this sounds/smells like...” which is only indirectly related to specific objects).

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In contrast to our other senses, olfactory information only has to be differentiable to be recognized by humans but does not need to be identifiable in terms of naming it which complicates research in this field due to limitations in language (Hamburger & Knauff, 2019). Simply put, nobody would describe the smell of a strawberry based on its furaneol component, smelling sweet and a little bit like caramel (only experts like sommeliers/wine stewards do so).

The weak relationship between odors and language is primarily due to the lateralization of brain areas involved in processing language and smell (Royet, 2004), as well as the difficulty of verbalizing odors due to the lack of precise mappings of olfactory representations to the language network in our brain (see Olofsson & Gottfried, 2015 for a review). However, in the latter case, language is a crucial factor for odor-color cross-modal associations and different approaches to talk about odors may also shape aspects of olfactory cognition (de Valk et al., 2017). An example for this is the Maniq language, which is spoken by a small group of nomadic hunters in southern Thailand and has a lexicon of more than a dozen terms specifically related to smell (Wnuk & Majid, 2014).

These findings are highly relevant when we look at artificial intelligence systems. They are already outstanding in (visual) pattern recognition, but they are still incapable of “understanding”; of giving meaning to something (i.e. semantics; e.g., Hamburger, 2020). Such systems are mainly based on language, visual context and visual patterns; they cannot use episodic memory, emotions, smell, or any other feature to complement the cognitive map. Those aspects lead to the fact that navigation is a multimodal process of our cognitive system.

Aside from the challenge of expressing odors in words, natural olfactory stimuli often consist of complex mixtures of numerous diverse components in varying proportions, which further complicates both, estimation of the dimensions of odor perception as well as research with odor stimuli (Ohloff, 1994).

An important factor in odor perception is the close relationship between the olfactory system and the trigeminal system (Stone et al., 1968; Cain & Murphy, 1980; Bouvet et al., 1987; Livermore et al., 1992). Beidler and Tucker (1956) published the first neurobiological description on olfactory and trigeminal responses. They said that a trigeminal nerve response was observed with most odors (Doty et al., 1978; Wysocki et al., 2003) that stimulated olfactory receptors, the feeling that underlies smell.

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This finding is an essential dimension of smell, which is often not appreciated. The trigeminal nerve, or cranial nerve V, is sensitive to mechanical and thermal stimulation. The branches innervate the nasal and oral cavities (Meredith, 1988). It is responsible for tears while cutting an onion or discomfort when we smell acetone, which is an intense and potentially dangerous smell.

However, not only the trigeminal nerve contributed to odor perception, but also cross-modal connections to the visual system, for example. Zellner and Whitten (1999) reported that adding color affected participants' perceived odor intensity when evaluating red-strawberry-flavored beverages. In this context, the intensity of certain colors played a significant role in modulating perceived odor intensity. Furthermore, it has already been demonstrated that people systematically (i.e., non-random) map odors and colors, with these cross-modal mappings being mostly based on semantic matches of recognizable odors.

Even artists, such as the French post-impressionist painter Cezanne, used/use this cross-modal link between colors and odors (Baudelaire, 1954; Taylor, 1963): "We see the depth, the smoothness, the softness, the hardness of objects; he believed that we can see their odor too" (Classen, 1998, p.128). Since then, many artists have used nonvisual perception in artworks and in everyday contexts (e.g., van Campen, 2014), as reported by Langner (1997; see also Smets and Overbeeke, 1989):

Many records already exist of the fact that human beings assign specific colors and shapes to smells. Nevertheless, could our sense of smell be structured so that we can also perceive smells as complete images? Are there specific natural laws or natural characteristics that permit images to become "odor images"? (Langner, 1997, p.193).

He eventually failed to assess how successful his approach to communicating olfactory attributes using color, form, and texture has been in his odor walk. However, several subsequent reports have suggested that people do indeed experience olfactory sensations when looking at pictures (i.e. mental imagery of odors).

These cross-modal correspondences between olfaction and color have become a major subject of recent research (i.e., Spence et al., 2010; Zellner, 2013; Spence, 2019, 2020). Those studies for

example have already investigated the cross-modal influences of color and odor in food and drinks as well as olfactory marketing strategies that subconsciously manipulate customers while shopping (Fründt, 2010; Hamburger & Herold, 2021). These and other studies could help to understand how human cognition and sensory consciousness works and how critical cross-modal relationships are. However, not only cross-modal relationships of the human olfactory system led to new applications e.g., in marketing. We believe that human wayfinding research with olfactory cues can lead to insights that go far beyond spatial orientation research and provide important results for research in other fields.

7.5 Current Research and Methodologies in Human Olfactory Navigation

Up to this point, we have highlighted the peculiarities of the olfactory system, suggesting its potential significance in human wayfinding. Research in this domain is still limited, but we have already mentioned some studies in the realm of human navigation using olfactory stimuli. In the following, we examine the experimental methods employed in these studies and present additional studies in this area. We aim to provide an overview of the research conducted so far and facilitate the (methodological) entry into the exploration of olfactory spatial navigation for future studies.

Taken together, we consider the following studies as being the most prominent and representative in olfactory navigation and landmark-based wayfinding research: Porter et al. (2007), Koutsoklenis & Papadopoulos (2011b), Moessanang et al. (2011), Jacobs et al. (2015), Dahmani et al. (2018), Raithel et al. (2023) and several studies by the Hamburger et al.'s research group (including Hamburger & Knauff, 2019; Arena & Hamburger, 2023; Schwarz & Hamburger, 2023a, 2023b).

In the study conducted by Porter et al. (2007), participants were tasked with tracing a scent trail made of a twine line soaked in chocolate essential oil (a 2% solution of the odorant diluted in water) across a grass field. The participants crawled and sniffed, mimicking the behavior of dogs. This research was groundbreaking in demonstrating that humans have the ability to track scents and can enhance this skill through practice. Additionally, the study revealed that human nostrils sample distinct spatial regions, and the process of scent-tracking is facilitated through comparisons between nostrils.

Koutsoklenis and Papadopoulos' (2011) study utilized a mixed-methods approach, starting with a focus-group interview with visually impaired participants. Subsequently, participants completed a

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questionnaire and engaged in a structured interview. In the focus-group interview, the researchers explored the olfactory cues visually impaired people use for navigation in urban environments. In the questionnaire, participants rated the frequency and perceived usefulness of each identified olfactory cue for wayfinding using a 4-point Likert scale. In the interview, participants discussed “How do you use this particular olfactory cue for wayfinding?” and “Which factors affect the use of this particular olfactory cue?”. Even though the study did not involve specific navigational tasks, it holds important findings for landmark-based wayfinding research by presenting a list of olfactory cues identified by visual impaired people as (useful) landmarks.

Moessnang and colleagues (2011) utilized a computer-controlled Burghart OMG6 olfactometer (Wedel, Germany) to facilitate standardized olfactory stimulation free from the influence of tactile or thermal cues. A notable feature was the independent delivery of scents to each nostril through two separate tubes. The onset and duration of olfactory stimuli were regulated using presentation software (Neurobehavioral Systems, Albany, US), and the olfactory cues used were phenyl ethyl alcohol (PEA) mixed with distilled water (1:10). In the experimental task, participants were instructed to quickly and accurately respond to whether a visual target stimulus appeared to the left or right of a fixation cross, with a distractor simultaneously appearing on the opposite side. The olfactory cue was presented to only one nostril (either the target or distractor side) 500ms before the visual cue. Subsequently, in a two-alternative forced-choice explicit localization task, participants had to determine whether an odorant was presented to the left or right nostril. Although Moessnang et al. (2011) did not incorporate a wayfinding or navigation task, we included this study in our review due to its innovative methodology involving a self-built olfactometer, particularly the cueing paradigm exploring the ability for directional smelling on an implicit level. Results indicated slower responses to congruently, compared to incongruently cued targets, but only chance-level performance in the explicit odor localization task (for more studies on odor localization tasks in humans, see e.g., Frasnelli et al., 2009, or Welge-Lüssen et al., 2014, though these are beyond the scope of the present review).

Jacobs et al. (2015) employed three essential oils as odorants in their study: sweet birch oil, anise oil, and clove bud oil. Each participant was provided with two sponges, each impregnated with 30 drops of a single essential oil (resulting in two different odors for each participant). The scented side of

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the sponges was placed facing up in open containers and used only once. Participants were guided to a randomly selected location within a room infused with both odors. After a brief period of exposure and spatial disorientation, participants were tasked with returning to this location. This study marked the first demonstration that humans possess the ability to navigate back to a specific location using only olfactory cues, similar to the homing abilities observed in pigeons.

As mentioned above, Dahmani and colleagues (2018) assessed olfactory identification, navigation, measured medial orbitofrontal cortex thickness and hippocampal volumes. For the evaluation of navigation, they employed two tasks: a wayfinding task and a dual-solution task, both utilizing visual landmark material (specifically, the 4-on-8 virtual maze task). In the context of odorant presentation and identification, they utilized the Monell Extended Sniffin' Sticks Identification Test (MONEX-40), which consists of 40 felt-tip pens infused with odors. During the test, sticks were placed under participants' noses for 1-2 seconds, and participants were required to select the correct word describing the odor from four presented options. While the neuroimaging findings focused solely on anatomical aspects, and the spatial navigation task itself did not involve odor cues, we included this study due to the methodology employed in the odor identification task. This methodology holds the potential for seamless integration into future wayfinding studies that incorporate odor cues, presenting a promising avenue for exploration.

In their fMRI study, Raithel et al. (2023) incorporated various measures, including odor ratings for intensity, pleasantness, and familiarity, an odor naming task, a four-alternative forced choice task (similar to the one described by Dahmani et al., 2018 above), and an odor navigation task. The odor stimuli comprised eight scents derived from either essential oils diluted in mineral oil or natural products, administered to participants through a custom-built olfactometer. In the odor navigation task, participants were required to locate the eight previously introduced odors as swiftly as possible within a virtual environment. The positions of the odors were indicated by white clouds in the virtual space, while the remaining spatial layout did not offer any directional cues. The results of this study are elaborated upon above in the context of "grid-like responses by odor landmark-based navigation" (refer to the section on *3.1 Evolutionary basis*).

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Finally, numerous studies by Hamburger and colleagues utilized similar methodological approaches and are therefore summarized here (see Hamburger & Knauff, 2019; Arena & Hamburger, 2023; Schwarz & Hamburger, 2023a, 2023b for more details). Studies comprised a learning phase, a wayfinding phase, and/or a *beaming* phase (i.e. teleportation) and/or a recognition phase. Participants were auto piloted through a virtual maze presented on a head-mounted display. At each intersection of the maze (varying between 12 and 18 intersections depending on the study), the video stopped, and landmarks were presented. Olfactory landmark information were selected from pilot studies (as is the case in Hamburger & Knauff, 2019) or from an evaluation study on odor quality by Hamburger and Herold (2021). They consisted of natural substances such as ground fruits and vegetables and synthetic fluids (e.g., fresh clothes spray) and were presented by hand via medical brown glass vials. In the learning phase, participants had to watch and remember the way through the maze with its landmarks at each intersection carefully. In the wayfinding phase the video paused at each intersection until participants indicated the route direction. The beaming phase functioned as a control condition where participants were teleported to an intersection of the maze (with the corresponding landmark being presented) and had to indicate the correct route direction in random order of the intersections. In the recognition phase, participants had to identify whether a presented stimulus was a landmark in the maze or a distractor (stimuli that did not appear in the maze).

Results of Hamburger and Knauff (2019) demonstrated that humans are able to navigate based on olfactory landmarks only. Arena and Hamburger (2023) compared wayfinding between visual, olfactory, and bimodal (visual x olfactory) landmarks and did not find significant differences in wayfinding performance across all conditions. As mentioned above, Schwarz and Hamburger (2023a) revealed an advantage of olfactory landmarks compared to visual landmarks over time. Finally, Schwarz and Hamburger (2023b) compared implicit and explicit processing of visual, olfactory, and bimodal (visual x olfactory) landmarks and revealed better olfactory wayfinding performance when odors were processed implicitly (= not correctly identified as landmarks in the recognition phase) rather than explicitly. For the visual condition, the exact opposite result was observed.

For more details on presentation times, odor concentration, manufacturers of olfactory stimuli, and similar aspects, we refer to the methods section and appendices of each study. Moreover, as we

advocate for the exploration of unconscious processes in human olfactory navigation, we recommend referring to Degel and Köster's (1999) implicit odor memory task, a methodology that has not yet been applied in spatial navigational contexts.

Taken together, these studies employ a diverse range of methods, ranging from questionnaires to laboratory and field settings. The results demonstrate that humans possess the ability to navigate using their sense of smell. However, they only mark the beginning of further, future research, as many questions remain open, such as the multimodal utilization of landmarks (Schwarz & Hamburger, 2023b), odor concentration effects, impact of odor composition on wayfinding (as reviewed by Young et al., 2020) or the use of the sense of smell in *real-world* navigation scenarios beyond experimental settings with odor plumes consisting of a mixture of odorants. These findings not only hold great potential for advancing our understanding of human orientation but also have implications across various domains beyond spatial cognition, given the unique characteristics of the sense of smell. In the subsequent discussion, we will offer a glimpse into the future of this topic and suggest potential applications.

7.6 From Current Knowledge to Future (Desirable) Research

Most people take their spatial abilities for granted or believe that they cannot orient themselves without navigational assistance. We are (mostly) just not aware of what our brain accomplishes day in and day out. We only become aware of it when we get lost (e.g., Dudchenko, 2010) or when something unexpected happens. Intuitively, we assume that we rely exclusively on visual information in our environment for orientation or directions. While the sense of smell was once important for detecting food and water, recognizing danger, and finding a suitable mate, we now believe that we have lost all these abilities. As we have highlighted in this review, however, this is a misconception. Like our other senses, the sense of smell still plays a crucial role in our lives; we are just not aware of it.

As emphasized, recent research shows that the human olfactory system is likely to be involved in human navigation but is underrepresented in spatial cognition research. We here like to emphasize the importance for future research to extend beyond the unimodal exploration of the olfactory system in navigational processes and instead delve into multimodal sensory processes that incorporate olfaction. For instance, studies on navigation in birds encompass the integration of olfactory, visual, and

mechanoreceptive inputs, exploring their collective contribution to the formation of mental maps (e.g., Abolaffio et al., 2018). Furthermore, a notable feature of successful odor navigation in the animal kingdom is the ability to employ a range of navigation strategies and swiftly switch between them based on the animals' needs, capabilities, and external stimuli, such as landmark-based wayfinding. This behavioral flexibility aligns with a key aspect of the cognitive map theory of spatial navigation proposed by Tolman (1948). To comprehensively understand navigational processes, more research on humans in this field is warranted (see, for example, Jacobs & Schenk, 2003; Møller & Köster, 2023).

We therefore advocate for further research into the sense of smell in relation to human navigation and thereby identify two significant advantages: On the one hand, the sense of smell has many peculiarities, making it ideal for the study of fundamental concepts in cognitive science (e.g., research on consciousness). On the other hand, the knowledge gained in this process will also be of great importance in many applications; for example, for new navigation systems or the construction of buildings improved for orientation (especially retirement homes, nursing homes, etc.). Thus, odors can be used as landmarks for wayfinding in buildings – especially for older people (e.g., van Campen, 2014), whose visual systems deteriorate as they age, and for people with certain illnesses, such as depression or schizophrenia, that lead to working memory deficits (e.g., Smith & Kosslyn, 2007).

Furthermore, the exploration of olfactory processes in human navigation holds even greater promise, extending beyond the comprehensive understanding of navigational processes or applications in navigation systems and architectural design.

Future research may therefore lead to a better understanding of the pathogenesis of olfactory dysfunction in neurological disorders, as well as in SARS-CoV-2/Covid-19 infections (Gane et al., 2020; Lechien et al., 2020). This is because decreased olfaction is often one of the most predictive symptoms of various diseases (e.g., of Covid-19; Gane et al., 2020; Lechien et al., 2020). With a better understanding of the pathogenesis, diseases can be better monitored and disease-modified odor-based therapies can be developed.

Furthermore, odor-based therapies for depression or other neural disorders, could take advantage of the unique and close connection between odors and emotions.

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In medicine, the olfactory system could be of great relevance as olfactory loss is one of the best predictors for mortality in older populations (Wilson et al., 2011; Gopinath et al., 2012; Pinto et al., 2014; Devanand et al., 2015). Studies already suggested that olfactory dysfunction may have potential as biomarkers in assessing the onset of Alzheimer's disease and future research could help to delay or prevent such central nervous system degenerations through early detection (Murphy, 1999; Kovacs, 2004; Craig-Schapiro et al., 2009; Jack et al., 2010; Sedghizadeh et al., 2020). Olfactory testing is also a potentially first-line non-invasive diagnostic measure of brain aging (Brai et al., 2020).

In social life, future research on the sense of smell can also be beneficial, because by knowing which odorants affect us positively, we can improve our performance, make everyday (work) life easier and reduce stress. This would involve all our senses and could enhance our overall well-being or lead to better positive intervention therapies (e.g., El Haj et al., 2018; Matsunaga et al., 2011).

As we highlighted in this review, research into olfactory information is important and long overdue. Therefore, we would like to motivate other researchers from various research areas to further explore the human sense of smell and propose wayfinding tasks as a promising approach to do so.

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7.9 Disclosure Statement

The authors report there are no competing interests to declare.

7.10 Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

7.11 Authors' Contributions

All authors contributed to the conception of this work. The first draft of the manuscript was initialized by the second author and further dealt with by the first author. All authors participated in writing the manuscript, commented on previous versions of the manuscript and revised it. All authors read and approved the final manuscript.

7.12 Compliance with Ethical Standards

Due to the nature of the review article and the fact that no data was collected for the current work, no individual ethical approval is required. The authors assume that all cited works were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. For self-citations the authors confirm that every work was approved by the local ethics committee (FB06, JLU Giessen).

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Part III.

General Discussion

8. Summary of the Results

This doctoral project systematically investigated the role of olfactory landmarks in human wayfinding and their interaction with other sensory modalities, particularly vision. Across three studies, the project tested the long-held assumption that the human sense of smell plays only a minor, or even no role in spatial orientation. My central hypothesis posited that, unlike vision, the human olfactory system is predominantly engaged in an implicit manner during navigation. The empirical findings support this assumption and show that olfactory information contribute to navigation in ways that differ fundamentally from visual cues (Publication 1). Olfactory signals often guide wayfinding outside conscious awareness (Publication 2), and their integration with visual information can produce compensatory effects on navigational performance (Publication 3).

The first study investigated the cognitive costs of switching between visual and olfactory landmarks during navigation. Previous work had shown that switching between auditory and visual landmarks does not necessarily impair performance, which raised the question of whether similar cross-modal flexibility would occur with olfaction. The results showed that this was not the case. Participants who learned a route with visual cues but were later tested with olfactory cues, or vice versa, took significantly longer to decide and made more navigation errors than those tested in the same modality in which they had learned. These findings suggest that visual and olfactory landmarks are processed by largely independent cognitive systems and that switching between them requires additional processing resources, hence worsening performance. Despite this cost, participants were still able to navigate successfully after a modality switch, indicating that the olfactory system can guide wayfinding even under changing conditions. The study therefore positions olfaction as a viable, although cognitively distinct, modality for landmark-based navigation.

The second study examined whether olfactory landmarks are processed more effectively implicitly rather than explicitly and compared this with visual and multimodal landmark conditions. Participants navigated a virtual maze at the initial assessment (t1) and completed the task again after a one-month delay (t2). The findings revealed a striking divergence between the senses. Navigation performance with olfactory landmarks was higher when participants did not consciously recognize or

recall those cues in the subsequent recognition test. In contrast, visual landmark-based wayfinding performance was higher when participants explicitly remembered them. These opposing patterns suggest that olfactory information supports navigation through implicit, long-term memory processes, whereas visual information relies more strongly on explicit recognition. In the multimodal condition navigation was highest when landmarks were remembered at the first testing and remained stable after the one-month delay. This study therefore highlights distinct processing mechanisms across the senses and indicates that olfactory cues can guide navigation even when they are not consciously accessible.

The third study offered a comprehensive review on human olfactory navigation. It synthesized evidence from neuroscience, psychology, and comparative research to address a longstanding misconception that humans possess a weak or poor sense of smell that plays no meaningful role in navigation. The review shows that olfactory cues are deeply intertwined with emotional and mnemonic processes due to direct connections between olfactory pathways and limbic structures. This neurobiological architecture allows smells to form exceptionally durable and emotionally potent memory traces, which can be deemed as highly relevant for navigation. The review also outlines why human olfactory navigation often operates implicitly, which may explain why its importance has been historically underestimated. Furthermore, it identifies gaps in current research, proposes methodological advances, and highlights broader applications of olfactory navigation research, for example in aromatherapy or the early detection of cognitive decline.

A coherent picture emerges from the three studies conducted in this doctoral project. Together, the findings demonstrate that olfactory information contributes to human wayfinding in ways that differ fundamentally from visual processing. Olfactory cues often operate outside conscious awareness, they support navigation even under modality switching, and they support navigation even when explicit recognition is not possible. Visual cues, in contrast, are most effective when consciously identified and remembered. Across all studies, a systematic functional asymmetry becomes evident. Vision and olfaction differ in memory demands, processing characteristics, and their respective contributions to accurate route decisions.

9. Discussion of the Results and Future Implications

9.1 Multimodal Integrative Model

These converging results lead to a broader theoretical question. If the senses contribute differently and with varying degrees of awareness, how exactly are these modalities organized within the cognitive architecture that supports human wayfinding? More specifically, how can we explain that olfactory cues guide navigation implicitly and over long intervals, whereas visual cues require explicit recognition, yet both contribute to successful spatial orientation? The empirical evidence suggests that the dominant frameworks used in landmark-based wayfinding research, which are largely vision-centered (e.g., Klippel & Winter, 2005; Montello, 2005; Siegel & White, 1975; Sorrows & Hirtle, 1999), do not fully capture the complexity revealed in this dissertation.

To address this gap, I introduce a *Multimodal Integrative Model* of cognitive map construction that integrates the findings of this dissertation with current work in sensory neuroscience and dual-process theories of cognition. This model conceptualizes landmark-based wayfinding as the result of interacting sensory pathways that differ in their accessibility to awareness, their memory characteristics, and their functional roles in navigation. It extends Daniel Kahneman's (2011) distinction between System 1 and System 2 by mapping these systems onto modality-specific processing routes in both vision and olfaction. The model highlights how implicit olfactory processing and explicit visual processing together form a complementary and compensatory architecture for human wayfinding, as illustrated in Figure 1, page 118.

Building on the systematic literature review and the series of experimental psychology studies, my model proposes that the senses interact and compensate for one another, going beyond the idea of parallel sensory channels and instead conceptualizing navigation as a dynamic interplay across modalities. It positions the olfactory system as an essential component within the broader sensory architecture rather than an evolutionary remnant of limited relevance, as already suggested by Gibson in 1966.

In the visual domain, the distinction between the dorsal and ventral streams is fundamental. The dorsal pathway processes automatic and rapid spatial information and therefore aligns closely with

System 1 (Kahneman, 2011; Milner & Goodale, 2008). The ventral pathway supports explicit and conscious recognition and identification of landmarks, which is essential for route planning and thus corresponds to System 2 (Kahneman, 2011; Milner & Goodale, 2008). This distinction aligns with Montello's (2005) conceptualization of wayfinding as the decision process of determining a route. Effective wayfinding therefore depends critically on explicit cognitive processing of environmental cues, functions that are fulfilled primarily by the ventral visual stream (Janzen & van Turenout, 2004). My findings support this distinction. When participants failed to recognize visual landmarks explicitly, navigational performance declined significantly (Publication 2; Schwarz & Hamburger, 2023), demonstrating the importance of conscious landmark memory for visual wayfinding.

Current advances in olfactory neuroscience reveal a strikingly similar organizational structure. Research identifies two distinct functional pathways in the olfactory system. One supports odor identification, while the other supports odor localization and automatic detection. Early work first described these differences primarily in terms of hemispheric specialization, suggesting that the two hemispheres contribute differently to odor processing (Royet & Plailly, 2004). Subsequent studies then expanded this view by proposing both parallel and hierarchical processing structures (Savic et al., 2000). More recent literature provides direct evidence that the olfactory system, like the visual system, comprises separate ventral and dorsal routes (Boot et al., 2024; Frasnelli et al., 2012). These pathways recruit different neural substrates and support different functions. Research by Porter and colleagues (2007) as well as Zhou and Chen (2009) show that the ability to determine which nostril detects an odor relies on different neural regions than the ability to identify or name the odor. Similar distinctions are discussed by Frasnelli and colleagues (2012). Together, these findings underscore an analogy between the visual and olfactory systems and support the existence of modality specific routes for rapid, automatic detection (System 1) as well as conscious identification and recognition (System 2).

At this point, a central question arises. If visual System 1 already provides highly efficient support for everyday navigation, for example when driving along a familiar route, why is the olfactory System 1 pathway still important and why does a multimodal system offer additional advantages? The literature consistently shows that visual System 1 processing is excellent for rapid, effortless, and well-practiced navigation (Goodale & Milner, 2006; Norman, 2002). It supports ongoing action and is closely

tied to the present perceptual context (Milner & Goodale, 2008). Its limitation, however, lies in its strongly online nature. Because visual System 1 is bound to immediate perceptual input, it has limited access to long-term memory (Kravitz et al., 2011; Medendorp et al., 2018). It supports efficient action in the moment but is not well suited for retrieving route information after longer delays or in the absence of visual cues.

The olfactory System 1 pathway operates in a fundamentally different way. Olfactory signals bypass the thalamus and project directly to limbic structures where they form memory traces that are durable and emotionally meaningful (Herz & Engen, 1996; Sullivan et al., 2015). This tight link to long-term memory allows odors to support the retrieval of spatial information even long after the initial exposure or in situations where visual cues are unavailable, representing a key advantage for multimodal integration. These findings are consistent with my master's thesis with Kai Hamburger (Schwarz & Hamburger, 2024a) on memory effects of olfactory versus visual landmarks. In that work, we show that olfactory landmarks support more persistent and retrievable route memories over longer retention intervals compared with visual landmarks, even when visual cues initially dominated route learning. Together, these results provide direct evidence that olfactory information constitutes a particularly stable and emotionally anchored substrate for spatial memory. The functional distinction underscores a key advantage of multimodal integration. Therefore, I postulate that while visual System 1 enables rapid, efficient navigation in familiar environments, olfactory System 1 contributes long-term stability and emotional tagging of spatial information. In conjunction they create a flexible and resilient architecture for spatial orientation.

On the other hand, explicit visual System 2 processing remains superior for deliberate and conscious landmark-based navigation, particularly under typical daily demands in unfamiliar environments, whereas navigation in familiar environments is often handled more automatically (Hamburger, 2020). In contrast, the implicit visual System 1 pathway shows reduced precision when it operates in isolation (see Publication 2; Schwarz & Hamburger, 2023). However, the olfactory System 1 compensates for this limitation by providing highly stable and emotion-linked access to memory and by being relatively resistant to interference. As a result, the interplay between explicit visual and implicit

olfactory cues can yield complementary strengths that are able to enhance navigational performance across different contexts.

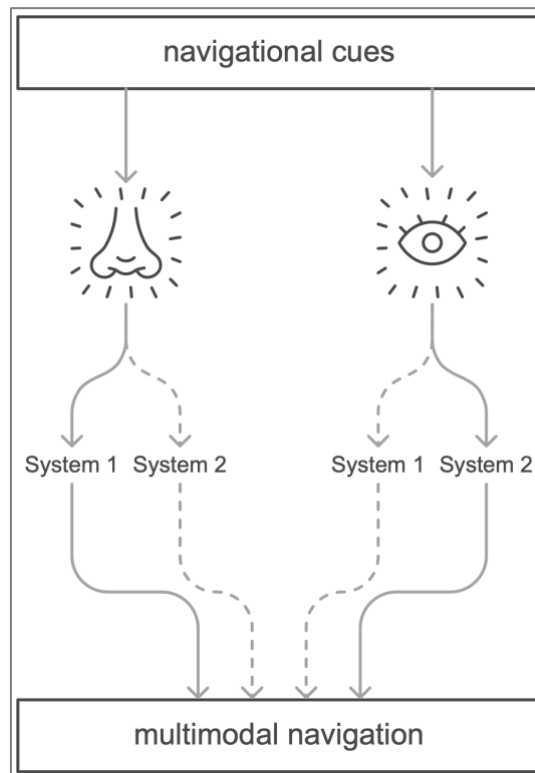
The switching costs observed in my empirical study (Publication 1; Schwarz & Hamburger, 2022) further support this separation of systems. When participants switched between visual and olfactory modalities, their navigation slowed down and became less accurate. These costs indicate that the underlying cognitive and memory mechanisms are distinct and not readily interchangeable. Earlier research on auditory and visual cues did not show such switching costs. This is likely because auditory cues are more readily integrated into explicit visuospatial representations within System 2, which reduces conflict when switching between these modalities. In contrast, the switch between visual and olfactory cues requires a shift between two fundamentally different processing systems.

In summary, the proposed *Multimodal Integrative Model* presents three core claims. First, olfactory System 1 processing is most effective for implicit and emotion-linked long-term spatial memory. Second, visual System 2 processing is essential for explicit route planning and conscious navigation. Third, the two systems operate through distinct neural pathways and cognitive mechanisms, and their multimodal interaction enhances navigation performance through complementarity and compensation, which aligns with Gibson's (1966) critique of treating the senses as independent channels, highlighting instead perception as integrated system.

This multimodal and dual-process perspective highlights that explicit visual recognition (System 2) is necessary for deliberate wayfinding, while implicit olfactory processing supports stable long-term memory for implicit spatial orientation (System 1). Effective human wayfinding therefore emerges from the interaction of explicit and implicit systems and from the complementary strengths of visual and olfactory modalities.

Figure 1

Multimodal Integrative Model



Note. Created with napkin.ai. Olfactory and visual cues are processed through distinct System 1 (implicit, automatic) and System 2 (explicit, controlled) pathways. Solid arrows represent the primary routes contributing most strongly to navigation; dashed arrows indicate weaker pathways. Olfactory System 1 (e.g., odor detection/localization) complements visual System 2 (e.g., deliberate wayfinding), while both modalities jointly support multimodal navigation despite operating separately, as reflected in behavioral switching costs.

9.2 Limitations

While this doctoral project provides important insights into the functional independence of olfactory processing and challenges the dominance of visual cues in wayfinding research, several limitations warrant careful consideration. These limitations pertain to theoretical framing, methodological constraints, ecological validity, and sample characteristics, highlighting directions for future research.

The *Multimodal Integrative Model* proposed in this dissertation builds on dual-system models (System 1: automatic/implicit; System 2: controlled/explicit; e.g., Kahneman & Frederick, 2005) and aims to explain modality-specific cognitive map construction. While this model provides a functional

lens to interpret modality differences, its application to sensory navigation has inherent constraints. Current debates in cognitive psychology suggest that the strict dichotomy of dual systems oversimplify cognitive processing. Categorizing processes as either fully automatic or fully controlled neglects the continuum of cognitive control proposed by Evans and Stanovich (2013). Moreover, critiques regarding the metaphorical nature of System 1 and System 2 (Keren & Schul, 2009) emphasize that these constructs do not map directly onto anatomically distinct neural circuits. In this dissertation, I have functionally assigned olfactory processing primarily to System 1 and visual processing to System 2. While this approach is useful for interpreting the empirical findings, it likely overlooks intermediate, integrative, or monitoring mechanisms that coordinate interactions between automatic and controlled pathways.

Moreover, the experimental paradigms employed in this project, including wayfinding tasks, reaction-time-based modality switching tasks and explicit recognition tests, were partly adapted from visual navigation research to enable cross-modal comparisons. Such adaptations, however, carry inherent limitations (for a comprehensive review, see Møller & Köster, 2023). Møller and Köster (2023) argue that core concepts and tasks developed for visual research are ill-suited to the study of human olfaction, as olfactory processing is predominantly implicit and largely operates outside conscious awareness. For example, studies cited by these authors, such as Pierzchajlo and Olofsson (2023), show that cue-target paradigms tend to overemphasize explicit, verbally or visually mediated memory processes, whereas genuine olfactory navigation in everyday contexts functions largely unconsciously and autonomously. Forcing participants to perform explicit recognition or identification tasks may therefore underestimate the actual navigational utility of olfactory cues. This methodological challenge highlights the need for paradigms tailored to the specific properties of olfaction. In particular, future research should consider physiological measures, such as skin conductance or heart rate, to capture implicit responses to olfactory landmarks. Complementary neuroimaging techniques, such as fMRI or EEG, could reveal differential activation patterns in limbic versus cortical regions during olfactory and visual navigation, thereby acknowledging the neurobiological uniqueness of olfactory processing. Finally, passive observation paradigms measuring wayfinding in naturalistic or virtual environments without explicitly directing attention to odors are especially promising for capturing unconscious

olfactory contributions to spatial behavior. Taken together, these methodological considerations underscore the necessity of a paradigm shift in olfactory navigation research. Studies should move beyond the uncritical adaptation of visual research methods and account for the intrinsic characteristics of olfactory perception, in order to fully capture its role in human wayfinding.

While methodological refinements are crucial to accurately capture the implicit contributions of olfactory cues, it is equally important to consider the contexts in which these cues operate. All data in this project were collected under highly controlled laboratory conditions, which ensured internal validity but limits generalizability. Real-world navigation occurs within complex, multisensory environments where olfactory, visual, haptic and auditory cues interact and compete for attention. It remains an open question whether olfactory pathways maintain their functional significance under such conditions. Future research should examine navigation in realistic settings, including urban “smellscapes” (e.g., Hamburger & Nuhn, 2023; Henshaw, 2013; Porteous, 1985), natural environments such as forests or deserts, and more immersive VR simulations (e.g., Yildirim et al., 2024), to assess the contribution of implicit olfactory processing to everyday wayfinding. Such studies could also clarify the evolutionary relevance of olfactory navigation in contexts where visual landmarks are sparse or ambiguous.

A further difference lies in the populations themselves: unlike our controlled laboratory sample, real-world individuals vary widely in age, sensory acuity, and cultural background, all of which shape how odors are perceived and used for spatial orientation (e.g., Ferdenzi et al., 2017; Keller et al., 2012). By focusing primarily on young, healthy adults, this project could not capture and represent this variability. Expanding research to more diverse populations in naturalistic contexts is therefore crucial to assess the generalizability of the model and to identify the conditions under which olfactory cues meaningfully guide navigation.

Taken together, these limitations do not diminish the central contribution of this doctoral project: showing that olfactory cues can play a supportive role in human navigation, primarily through automatic, implicit processing. Rather, they underscore the need to advance theoretical models, establish olfaction-specific methodologies, and rigorously evaluate ecological validity. Addressing these limitations will advance our understanding of multisensory influences in human navigation and highlight the olfactory sense as a fundamental, yet often overlooked, component of spatial cognition.

Finally, future research may help to further develop the *Multimodal Integrative Model* proposed here, exploring its applicability across different sensory modalities and environmental contexts.

9.3 Future Implications

Although this doctoral project was grounded in basic research, its findings carry significant implications for future scientific inquiry as well as for a range of applied fields. By demonstrating the functional independence and robustness of olfactory processing in human wayfinding, the project opens a promising research domain with relevance for disciplines such as architecture, design, geography, information processing, marketing, and biology. Spatial orientation is a fundamental cognitive process essential for everyday behavior (e.g., Montello, 2005), and the present findings extend its interdisciplinary significance.

For example, they offer new perspectives for aging research, given that olfactory dysfunction has been identified as a strong predictor of five-year mortality (Devanand et al., 2015). In applied mobility contexts, the deliberate use of olfactory cues may influence behavior in car-sharing or vehicle rental systems and could even enhance road safety (Schwarz & Hamburger, 2024b). These insights are also relevant for settings such as daycare centers, senior housing, and nursing facilities, where spatial disorientation is common and where carefully designed olfactory environments may support cognitive well-being (Croy et al., 2014).

The practical implications become particularly clear when considering architectural and urban environments. Despite its importance, olfaction has long been neglected in the design of spatial settings (Spence, 2020). The findings of my project suggest that olfactory cues can be deliberately placed to support navigation in visually complex or uniform spaces such as hospitals, subway stations, or large shopping centers. Because olfactory processing is largely implicit, such cues can guide orientation even under high cognitive load when controlled visual processing is limited (Schwarz et al., 2025). At the same time, they act as emotional anchors that enhance mood and create a sense of place, which can indirectly support orientation and well-being.

These insights also generate important hypotheses for clinical and cognitive neuroscience. Since olfactory impairment often precedes the onset of neurodegenerative diseases such as Alzheimer's and

Parkinson's (Croy et al., 2014; Doty, 2017), implicit olfactory navigation tasks may serve as more sensitive early indicators than traditional explicit smell tests (Schwarz & Hamburger, 2023). In rehabilitation contexts, training with olfactory landmarks could provide a non-visual means of enhancing spatial cognition in individuals with impaired visual or explicit memory systems, offering new therapeutic avenues.

Taken together, the findings of this doctoral project lay the foundation for innovative applications across both basic and applied domains.

10. Conclusion

This cumulative dissertation challenges the vision-dominant paradigm in wayfinding research by proposing a *Multimodal Integrative Model* for landmark processing. Across two empirical studies and a systematic review conducted as part of this dissertation, I examined how visual and olfactory cues contribute to navigation. Findings show that human wayfinding relies on functionally distinct systems modulated by sensory input: visual landmarks engage mainly in explicit memory (System 2), whereas olfactory landmarks most likely follow the evolutionarily older, implicit pathway (System 1). Evidence for this separation comes from contrasting performance patterns: wayfinding improves when olfactory cues are processed implicitly and visual cues explicitly, while switching between modalities incurs costs. Integrating information across multiple sensory modalities can stabilize performance, as the strengths of one system compensate for the limitations of another. This complementary interaction of implicit and explicit systems underscores the unique contribution of olfactory cues to navigation. In line with Gandalf's advice in *The Lord of the Rings*, "If in doubt, always follow your nose", these findings show that following one's nose could be much more than just a metaphor: olfactory information meaningfully supports spatial orientation, guiding behavior in ways that complement conscious, visually driven strategies.

11. References

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12. List of all Publications⁹

- Schwarz, M.**, & Hamburger, K. (under review). *Influence of negative and positive ambient scent on wayfinding performance and implicit memory* [Manuscript under review]. Next Research.
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⁹ The list of publications is sorted chronologically, not alphabetically.

- Schwarz, M., & Hamburger, K.** (2023). Implicit versus explicit processing of visual, olfactory, and multimodal landmark information in human wayfinding. *Frontiers in Psychology, 14*, 1285034. <https://doi.org/10.3389/fpsyg.2023.1285034>
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13. Declaration of Authorship

I hereby declare that I have prepared the thesis at hand independently and without undue aid or the use of any resources other than indicated within the thesis. All parts of my thesis taken either verbatim or analogously from the published or unpublished works of or based on oral communications with others are indicated as such. Regarding all aspects of my scientific enquiries as they appear in my thesis, I have upheld the tenets of good scientific practice as laid out in the "Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis" and complied with the precept of ethics, data protection and animal welfare. I declare that I have neither directly nor indirectly given monetary or any other valuable considerations to others in connection with the thesis at hand. I declare that I have not presented the thesis at hand, either in an identical or similar form, to an examination office or agency in Germany or any other country as part of any examination or degree. All materials from other sources as well as all works performed by others used or directly referenced within the thesis at hand have been indicated as such. In particular, all persons involved directly or indirectly in the development of the thesis at hand have been named. I agree with the screening of my thesis for plagiarism via offline or online detection-software.

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